

The University of Chicago

THE SEDIMENTS OF
BUZZARDS BAY AND CAPE COD BAY
MASSACHUSETTS

A PART OF A DISSERTATION SUBMITTED TO
THE FACULTY OF THE DIVISION OF THE
PHYSICAL SCIENCES IN CANDIDACY FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

1940

By
JACK LUIN HOUGH

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SEDIMENTS OF BUZZARDS BAY, MASSACHUSETTS

J. L. HOUGH

University of Chicago, Chicago, Illinois

Contribution No. 187, Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

ABSTRACT

The modern sediments of the bay are described principally by the use of quantitative data derived from mechanical, mineralogical and chemical analyses. The environment of the sediment and its source and mode of deposition are discussed.

INTRODUCTION

This study is a part of the program of the Woods Hole Oceanographic Institution relating to the investigation of sediments of the Continental Shelf and coastal waters of the eastern United States. The field work and a part of the laboratory work were done under the auspices of the Oceanographic Institution during the summer of 1934. The remainder of the laboratory work was done subsequently in the sedimentation laboratory of the University of Chicago.

Buzzards Bay is a deep indentation of the shoreline which marks the western boundary of Cape Cod (fig. 1). The bay is 28 miles long, averages about 8 miles in width, and has an average depth of about 50 feet in its central portion. The surface area of the bay is 235 square miles, and the area of the land draining into it is 385 square miles, only 1.64 times as great. The relief of the land draining into Buzzards Bay is low, the maximum elevation in the watershed being between 200 and 300 feet. This land is gently rolling and poorly drained with numerous lakes and marshes. There is a good cover of vegetation and the soils are sandy and porous so that erosion takes place slowly.

The northwestern and northern shores are deeply indented whereas the eastern and southeastern shores are more regular. A chain of islands separated by tidal

channels forms the southeastern side of the bay. The Cape Cod Ship Canal connects the head of Buzzards Bay with Cape Cod Bay to the northeast. The water in the bay has nearly the same concentration of salt as the adjacent ocean water, since tidal currents cause frequent interchange between the two bodies and there are no large streams bringing in fresh water.

The northwestern shore of Buzzards Bay represents, roughly, the edge of a shield of igneous rocks and Paleozoic sediments that constitutes the bulk of the New England Lowland. A few deep well borings show that the surface of the crystalline mass extends beneath Cape Cod to the east and south. The bed rock of the northwestern shore of Buzzards Bay is the Dedham granodiorite, upon which lies a shallow, discontinuous cover of glacial drift and recent sediment. Thick deposits of glacial drift form the other shores of the bay. A frontal moraine extends from the northeastern corner of the bay southward to Woods Hole (fig. 2), turns southwestward and forms the Elizabeth Islands that separate the bay from Vineyard Sound. It may be traced in shoals lying southwest of the islands for a distance of 12 miles. This moraine is the inner one of two prominent ridges of drift making up a large part of Cape Cod and the New England Islands.

GEOLOGIC HISTORY OF THE REGION

Nantucket, Martha's Vineyard, Block Island and Long Island mark the edge of an almost completely submerged cuesta of Tertiary and Cretaceous rocks which formerly extended farther northward and overlaid the older rocks of the mainland. The more or less continuous depression between this cuesta and the New Eng-

southern New England. The bottoms of Buzzards Bay and similar features must, therefore, have been exposed to subaerial processes for at least a short time.

TOPOGRAPHY OF THE BOTTOM

The bottom topography (fig. 2) when considered in detail is irregular and reflects the effects of glaciation. Submerged ridges parallel to the Elizabeth chain ap-

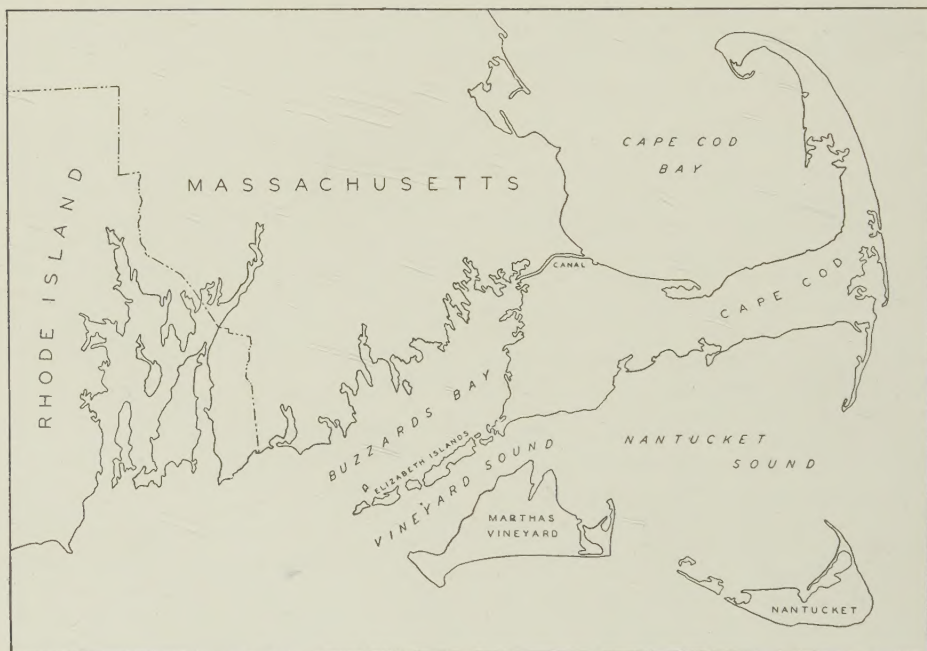


FIG. 1.—Index map showing location of Buzzards Bay.

land oldland probably was formed by subaerial erosion during a time of extreme lowering of sealevel in the late Tertiary (Veatch, 1906). Pleistocene glaciation modified the surface of the oldland to some small degree and formed the system of moraines and outwash plains which constitute the bulk of Cape Cod and the New England Islands. In late Pleistocene time, the sea was perhaps as much as 200 feet below its present level when the glacial ice disappeared from

parently are poorly developed recessional moraines. Certain details of topography, such as the deep channel leading seaward from the mouth of the bay and the extension of the 40-foot contour toward the head of the bay, may have resulted from the late glacial subaerial erosion.

The greater part of the bay is less than 50 feet deep, but a depression near Quicks Hole attains a depth of 126 feet and channels in the mouth of the bay contain depths of 100 to 140 feet. The

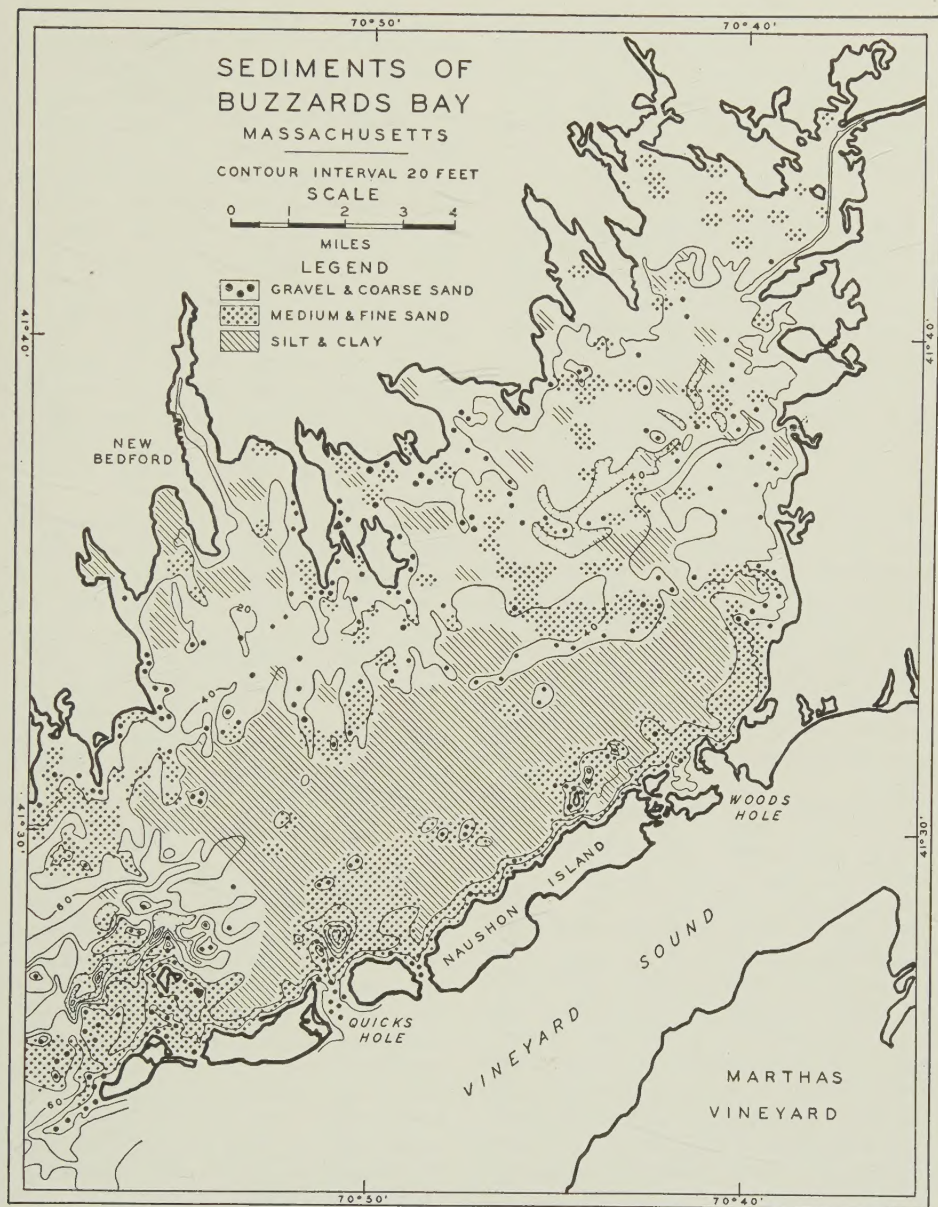


FIG. 2.—Sediments of Buzzards Bay. Shoreline and topography based on U. S. Coast & Geodetic Survey Chart No. 249, July, 1933.

low ridges forming the promontories of the northwest shore are roughly parallel to the direction of ice-movement during

glaciation. At the head of the bay these ridges trend southeastward whereas at the mouth of the bay they trend nearly

southward. An orientation roughly normal to the line of the moraine on the opposite side of the bay is thus maintained. Shoals in the northwestern side of the bay mark the extensions of the ridges under water.

FIELD METHODS

Field work was done from the *Asterias*, a 40-foot power boat of fisherman type owned by the Oceanographic Institution. Bottom sampling apparatus consisted of coring tubes, a clamshell snapper and a Stetson-Iselin sampler (Hough 1939).

Two hundred and twenty-five samples were taken, most of them serially along lines crossing the bay at intervals from near its head to its mouth. In running these lines, departure was taken from some fixed point such as a buoy. The distance between stations was measured by taking the travel time of the boat which was operated at a constant speed between stations, and the lines were terminated at some other fixed point. In most of the series, the distance between samples was one-half mile. Coarse-grained sediments were stored in glass jars and cores of fine-grained sediments were wrapped in newspapers.

LABORATORY METHODS

The mechanical composition of the sediments was studied by the sieving (Wentworth, 1926) and the pipette (Krumbein, 1932) methods. The sieves used were graduated on the basis of the square root of 2. The weight percentages of material in the different size grades were calculated as cumulative percentages, and cumulative curves were drawn from which the first quartile (Q_1), median (M) and third quartile (Q_3) diameters were read. The statistical constants devised by Trask (1932) for sorting and skewness were then calculated for each sample. The sorting factor, $So.$, equals $\sqrt{Q_3/Q_1}$ and the skewness, $Sk.$, equals $Q_1 \times Q_3 / M^2$. In these equations Q_3 is greater than Q_1 . The log of the skewness (to the base 10) is used in presenting the data. The results of the mechanical analyses are given in table 1.

In making a mineralogical study, small-sized separates of one size-grade common to several samples were obtained by use of a miniature sample-splitter of the Jones type (Otto, 1933). Separation into light and heavy fractions was then made with bromoform of specific gravity of 2.76. The fractions were mounted on microscope slides in piperine. This medium was used because its index of refraction falls near the center of the range of the indices of the heavy minerals. The minerals were identified by a petrographic microscope, and their frequencies were determined by counting the number of each species found in making three or four traverses on each slide. Between 100 and 300 grains were counted in each slide.

The acid-soluble material (assumed to be largely calcium carbonate) was determined by weighing the dried material, treating it with dilute hydrochloric acid (1:4), filtering, drying, and reweighing.

Data on the organic content of the sediments were supplied by H. R. Seiwel, chemist of the Woods Hole Oceanographic Institution, who made the determinations on samples which he collected for the purpose.

BOTTOM SEDIMENTS

The sediments of Buzzards Bay range from black, fine silts to clean, washed gravels and boulders. Cumulative curves of all the sediments analyzed were plotted on one graph. This showed a more or less regular gradation from fine-grained, rather poorly sorted sediments to coarse-grained, well sorted sediments. Since there is no distinct grouping of the samples into types, an arbitrary separation is made on the basis of the Wentworth classification. Gravel and coarse sand (median diameter greater than 0.500 mm.) are grouped together, sands of medium and fine grade (median diameter 0.500 to 0.061 mm.) are placed in a second group and silts and clays (median diameter less than 0.061 mm.) form a third. The distribution of these three groups in the bay is shown in figure 2.

TABLE 1. *Mechanical composition of sediments of Buzzards Bay, Massachusetts*

Sample No.	Latitude	Longitude	Depth in feet	Statistical constants				Log Sk.	Remarks
				Diameters in mm. Q1	Med.	Q3	So.		
1	41°39'08"	70°45'07"	19	.170	.250	.360	1.456	— .010	
2	39'08"	44'47"	22	.142	.211	.310	1.478	— .004	
3	39'08"	44'07"	24	.185	.280	.490	1.628	+ .064	
4	39'09"	43'28"	23	.260	.382	.560	1.470	.000	
5	39'10"	42'48"	19	.381	.586	.985	1.605	+ .038	
6	39'11"	42'08"	25	.010	.047	.111	3.263	— .286	
7	39'12"	41'30"	42	.211	.413	.680	1.794	— .077	
8	39'12"	40'51"	30	.180	.302	.537	1.726	+ .026	
9	39'09"	40'22"							Hard Bottom
10	38'47"	40'48"	29	.182	.381	.610	1.828	— .116	
11	38'24"	41'13"	33	.203	.428	.710	1.870	— .104	
12	37'54"	42'00"	42	.051	.366	.645	3.560	— .595	
13	37'58"	42'22"	18	.439	.579	.724	1.280	— .022	
14	38'08"	42'37"	26	.325	.510	.745	1.512	— .031	
15	38'50"	44'24"	28	.187	.286	.438	1.530	— .001	
16	38'20"	44'18"	30	.231	.337	.457	1.410	— .032	
17	37'49"	44'14"	29	.050	.302	.480	3.100	— .582	
18	37'18"	44'08"	36	.239	.321	.437	1.353	+ .004	
19	36'22"	43'48"	31		> .500				*
20	35'55"	43'38"	38		< .061				*
21	35'27"	43'27"	39		> .061				*
22	35'00"	43'17"	38		> .061				*
23	34'32"	43'07"	39	.195	.267	.362	1.360	— .005	
24	34'05"	42'56"	33		> .061				*
25	33'52"	42'46"	41		> .061				*
26	33'22"	42'37"	46		< .061				*
27	32'53"	42'25"	46		< .061				*
28	32'24"	42'12"	42		< .061				*
29	31'55"	41'59"	34	.105	.241	.410	1.980	— .130	
30	35'30"	40'09"	28						Hard Bottom
31	35'17"	40'40"	39	.283	.482	.661	1.530	— .094	
32	34'43"	41'44"	45	.005	.014	.042	2.920	.000	
33	34'26"	42'18"	37		< .500				*
34	34'17"	43'33"	36		< .500				*
35	34'30"	44'09"	41		< .500				*
36	35'02"	40'10"	51	.006	.021	.051	2.890	— .135	
37	34'45"	40'11"	33		< .500				*
38	34'34"	39'51"	28	.354	.592	.968	1.654	— .010	
39	34'38"	39'32"	38	.350	.567	.910	1.612	— .004	
40	34'45"	39'11"	36	.325	.714	1.425	2.092	— .040	
41	34'07"	40'24"	41		< .500				*
42	41°33'08"	70°40'59"	46		< .061				
43	32'10"	41'34"	38		< .500				*
44	33'47"	42'23"	46		< .061				
45	33'28"	41'48"	49	.006	.018	.049	2.780	+ .004	
46	33'11"	41'14"	47		> .061				*
47	32'54"	40'38"	37		> .061				*
48	32'44"	40'19"	33		> .061				*
49	32'36"	40'04"	30		> .061				*
50	36'44"	47'31"	23	.200	.255	.323	1.270	— .002	
51	36'15"	47'12"	29	.219	.300	.409	1.370	— .002	
52	35'52"	46'45"	37		.110	.246			*
53	35'28"	46'14"	37	.212	.326	.483	1.510	— .015	
54	35'05"	45'53"	37	.276	.426	.617	1.490	— .030	
55	34'42"	45'26"	39	.258	.404	.616	1.540	— .057	

* Determinations by partial analysis and inspection.

Sample No.	Latitude	Longitude	Depth in feet	Statistical constants				Log Sk.	Remarks
				Diameters in mm. Q1	Med.	Q3	So.		
56	34'19"	45'00"	43	.230	.352	.556	1.550	+.013	
57	33'56"	44'34"	43	.202	.334	.530	1.620	-.020	
58	33'33"	44'08"	45	.005	.010	.020	2.078	-.020	
59	33'08"	43'42"	46	.004	.008	.017	2.130	-.012	
60	32'46"	43'16"	47		<.074				*
61	32'22"	42'50"	45		.181				*
62	31'58"	42'23"	35	.222	.433	.791	1.890	-.024	
63	31'41"	41'42"	35	.178	.245	.345	1.391	+.009	
64	31'28"	41'39"	24						Gravel
65	34'51"	48'36"	28	.121	.200	.300	1.580	-.043	
66	34'31"	48'10"	28	.240	.377	2.310	3.100	+.591	
67	34'10"	47'45"	36	.177	.305	.490	1.660	-.031	
68	33'06"	46'22"	44		<.074				*
69	32'44"	45'55"	46		<.074				*
70	32'22"	45'29"	46		<.074				*
71	32'00"	45'02"	47		<.074				*
72	31'38"	44'35"	48	.222	.295	.426	1.380	+.037	
73	33'49"	50'19"	34	.125	.177	.254	1.420	+.005	
74	33'25"	49'54"	48		.165	.262			
75	33'02"	49'29"	30	.515	.670	.985	1.380	+.053	
76	32'38"	49'02"	47	.007	.020	.049	2.690	-.087	
77	32'16"	48'37"	49	.005	.014	.035	2.626	-.056	
78	31'52"	48'12"	51	.005	.016	.037	2.615	-.107	
79	31'29"	47'47"	48	.008	.024	.053	2.624	-.163	
80	30'44"	46'53"	45	.006	.025	.055	2.940	-.253	
81	30'20"	46'28"	45		<.061				*
82	29'57"	46'03"	48	.007	.024	.050	2.630	-.200	
83	29'34"	45'36"	30	.015	.077	.240	4.050	-.226	
84	31'30"	47'18"	48		<.061				*
85	31'47"	46'46"	46	.007	.021	.042	2.440	-.180	
86	31'53"	46'12"	47		<.061				*
87	32'14"	44'24"	48		<.061				*
88	41°31'53"	70°54'27"	40						Gravel
89	31'53"	53'46"	32	.043	.228	.480	3.340	-.390	
90	31'52"	53'04"	46		<.061				*
91	31'52"	52'20"	47	.008	.029	.059	2.710	-.252	
92	31'52"	51'38"	37	.024	.115	.222	3.060	-.397	
93	31'51"	51'17"	47	.045	.158	.254	2.400	-.345	
94	31'55"	50'44"	47	.121	.176	.247	1.428	-.017	
95	32'02"	50'31"	25						One pebble
96	32'07"	50'19"	40	.167	.217	.307	1.355	+.037	
97	31'35"	50'07"	46		<.061				*
98	31'22"	49'30"	54		<.061				*
99	30'09"	48'53"	50		<.061				*
100	30'58"	48'04"	47		<.061				*
101	31'01"	47'31"	46		<.061				*
102	31'03"	46'53"	46		<.061				*
103	31'06"	46'17"	46	.005	.014	.037	2.690	-.020	
104	31'09"	45'40"	48	.050	.202	.370	2.720	-.343	
105	31'12"	45'05"	46	.178	.353	.579	1.800	-.080	
106	31'13"	44'47"	42	.215	.315	.468	1.480	+.006	
107	31'14"	44'29"	41	.223	.295	.407	1.350	+.018	
108	31'19"	43'57"	28	.187	.341	.550	1.710	-.051	
109	31'25"	43'17"	43		<.061				*
110	31'27"	42'57"	44		<.061				*
111	31'30"	42'37"	39		.062	.238			*
112	31'32"	42'17"	44	.155	.230	.308	1.410	-.045	
113	30'17"	45'40"	45		<.061				*
114	30'36"	45'06"	46	.005	.014	.038	2.700	+.004	

Sample No.	Latitude	Longitude	Depth in feet	Statistical constants				Log Sk.	Remarks
				Diameters in mm.					
				Q1	Med.	Q3	So.		
115	30'37"	47'54"	46	.016	.041	.070	2.060	-.188	
116	30'04"	47'19"	38	.012	.038	.066	2.320	-.250	
117	29'43"	46'56"	43	.009	.036	.060	2.580	-.370	
118	29'22"	46'34"	45	.008	.032	.055	2.720	-.377	
119	29'11"	46'23"	18	.172	.422	1.195	2.640	+.065	
120	31'00"	50'23"	56	.009	.030	.069	2.840	-.173	
121	30'52"	49'59"	56	.011	.039	.079	2.680	-.246	
122	30'36"	49'27"	52	.025	.080	.110	2.100	-.367	
123	30'18"	48'57"	51	.029	.089	.123	2.052	-.342	
124	30'00"	48'27"	48	.013	.051	.087	2.770	-.362	
125	29'42"	47'57"	44	.009	.035	.066	2.740	-.314	
126	29'24"	47'27"	46	.032	.147	.382	3.450	-.248	
127	29'05"	46'56"	42	.049	.135	.251	2.260	-.172	
128	30'33"	50'27"	56		<.061				*
129	30'07"	50'35"	56		<.061				*
130	29'41"	50'42"	54		<.061				*
131	29'15"	50'49"	51		>.061				*
132	28'49"	50'56"	51		>.061				*
133	41°28'23"	70°51'03"	63	.218	.320	.520	1.540	+.045	
134	27'59"	51'09"	80	.176	.256	.480	1.650	+.110	
135	27'57"	51'04"	100	.137	.431	.818	2.440	-.219	
136	28'10"	50'52"	79	.201	.287	1.370	2.610	+.526	
137	28'23"	50'40"	68	.164	.210	.318	1.390	+.072	
138	28'36"	50'28"	53	.114	.158	.189	1.290	-.063	
139	29'02"	50'05"	53		>.061				*
140	29'27"	49'39"	52		>.061				*
141	29'49"	49'15"	53		>.061				*
142	30'20"	48'51"	51						See Table 3
143	27'47"	51'08"	62	.198	.262	.350	1.330	+.005	
144	27'54"	50'48"	122	.182	.254	.520	1.690	+.165	
145	28'00"	50'29"	80	.152	.198	.265	1.319	+.012	
146	28'06"	50'10"	54	.100	.138	.180	1.340	-.025	
147	27'22"	48'40"	18						Gravel
148	27'36"	48'49"	25	.162	.200	.294	1.348	+.075	
149	27'51"	48'58"	39	.040	.078	.120	1.730	-.104	
150	28'19"	49'17"	39	.037	.080	.117	1.780	-.172	
151	27'35"	50'58"	66	.205	.725	4.116	1.418	+.207	
152	27'27"	50'40"	54	.148	.188	.250	1.300	+.019	
153	27'13"	50'51"	52	.165	.245	.427	1.608	+.069	
154	27'02"	50'55"	45						Gravel & shells
155	26'52"	50'52"	38						Gravel & algae
156	26'35"	50'52"	38						Gravel & shells
157	26'13"	50'40"	45						Gravel, shells & algae
158	26'03"	50'25"	40						Sand & shells
159	25'56"	50'05"	47						Sand & shells
160	31'00"	54'45"	60	.012	.044	.173	3.880	+.008	
161	30'50"	54'40"	30						Hard bottom
162	30'44"	54'40"	9						Hard bottom
163	30'36"	54'36"	20	.035	1.156	2.900	2.880	-.120	
164	30'29"	53'56"	52		<.061				*
165	30'22"	53'15"	52		<.061				*
166	30'13"	52'33"	57		<.061				*
167	30'00"	51'12"	56		<.061				*
168	30'24"	54'25"	39	.302	.575	1.045	1.860	-.020	
169	30'02"	54'02"	53		<.061	.068			*
170	29'40"	53'40"	63		<.061	.098			*
171	28'56"	52'56"	58		<.061	.102			*
172	28'34"	52'34"	57		<.061	.070			*

Sample No.	Latitude	Longitude	Depth in feet	Statistical constants				Log Sk.	Remarks
				Diameters in mm. Q1	Med.	Q3	So.		
173	28'11"	52'11"	56		<.061	.084			*
174	27'44"	51'45"	28	.187	.287	.417	1.494	-.051	
175	27'36"	51'34"	33	.109	.144	.177	1.272	-.031	
176	27'30"	51'52"	61		<.061				*
177	27'18"	52'27"	48		<.061				*
178	27'05"	53'03"	44		<.061				*
179	26'53"	53'39"	39		<.061				*
180	26'26"	54'15"	20	.277	.467	.890	1.190	+.054	
181	26'20"	55'40"	18						Pebbles, sand & shells
182	30'35"	55'14"	40	.035	.200	.455	3.600	-.400	
183	30'05"	55'12"	53	.016	.034	.095	2.420	+.111	
184	31'25"	55'30"	38	.092	.332	.620	2.600	-.287	
185	31'05"	55'48"	48	.154	.282	.426	1.660	-.081	
186	30'41"	56'08"	50	.033	.148	.328	3.180	-.311	
187	30'16"	56'29"	38	.131	.253	.485	1.920	-.004	
188	29'52"	56'51"	36	.339	.462	.602	1.330	-.020	
189	29'13"	57'22"	28						(1st trial) 1 pebble
190	29'13"	57'22"	30	.190	.310	2.800	3.830	+.771	(2nd trial)
191	28'39"	57'12"	84	.010	.040	.121	3.405	-.112	
192	28'11"	57'02"	101	.026	.102	.281	3.260	-.146	
193	27'44"	56'52"	57	.311	.451	.628	1.421	-.011	
194	27'30"	56'47"	83	.172	.305	.526	1.750	-.011	
195	27'15"	56'42"	82	.297	.490	.922	1.765	-.058	
196	26'47"	56'32"	50	.185	.320	.605	1.805	+.095	
197	26'19"	56'22"	45	.130	.220	.414	1.780	+.045	
198	27'02"	57'10"	145	.145	.262	.371	1.600	-.104	

It may be seen that the coarser sediments generally occur in exposed areas near shore and on topographic highs. The finer sediments occur in the deeper south-central portion of the bay and in the protected embayments of the northwest shore. The deep holes in the mouth of the bay and the depression near Quicks Hole contain coarse sediment and, therefore, present a special problem.

The relation between median diameter of the sediment and depth of water was investigated by plotting these two figures for each sample on a graph. No significant degree of correlation was found. Differences in the degree of exposure to wave and current action on the irregular bottom are believed to be of greater importance than absolute depth in determining the characteristics of the sediments.

The sorting factor was plotted against median diameter in a graph (fig. 3),

which indicates clearly the tendency for the finer sediments to be poorly sorted and the coarser sediments to be well sorted.¹ This graph shows a concentration of points between the sorting values 2.5 and 3.0, below a median diameter value of 0.061 mm. Another group of points is located between the sorting values 1.35 and 2.00 above the median diameter value 0.130 mm. There are no sediments with a median diameter less than 0.061 mm. having sorting factors less than 2.00, and comparatively few of

¹ On the basis of 170 samples of marine sediments, Trask set up the following classification of sorting: well sorted sediments are those with So. less than 2.5, normally sorted sediments are those with So. between 2.5 and 4.5, and poorly sorted sediments are those with So. greater than 4.5. (Trask, 1932, p. 72) Stetson gives an average of 1.45 for well-sorted, near-shore marine sediments. (Stetson, 1937)

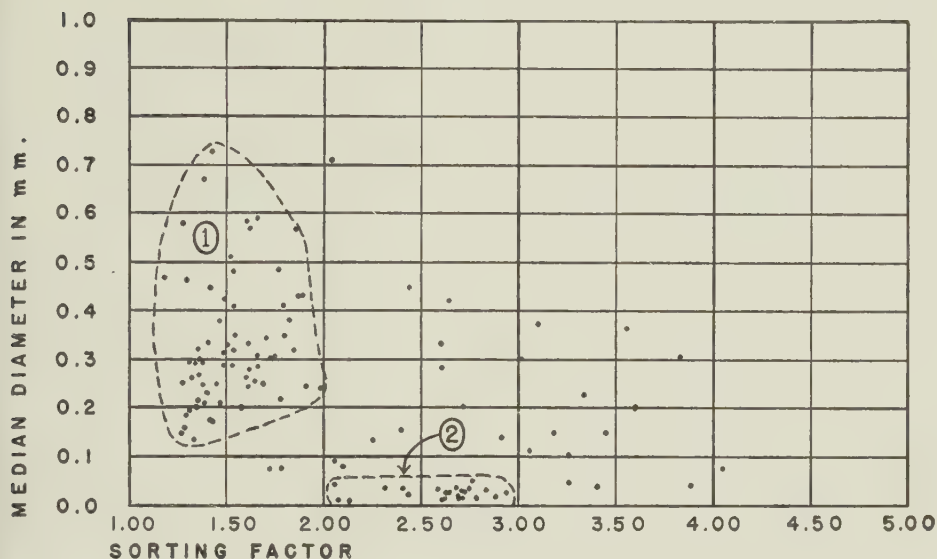


FIG. 3.—Graph of median diameter plotted against sorting factor.

the coarser sediments have sorting factors greater than 2.00.

The log of skewness was plotted against median diameter in another

graph (fig. 4). This shows a group of points between the median diameter values 0.130 and 0.600 mm. having logs of skewness not exceeding plus or minus

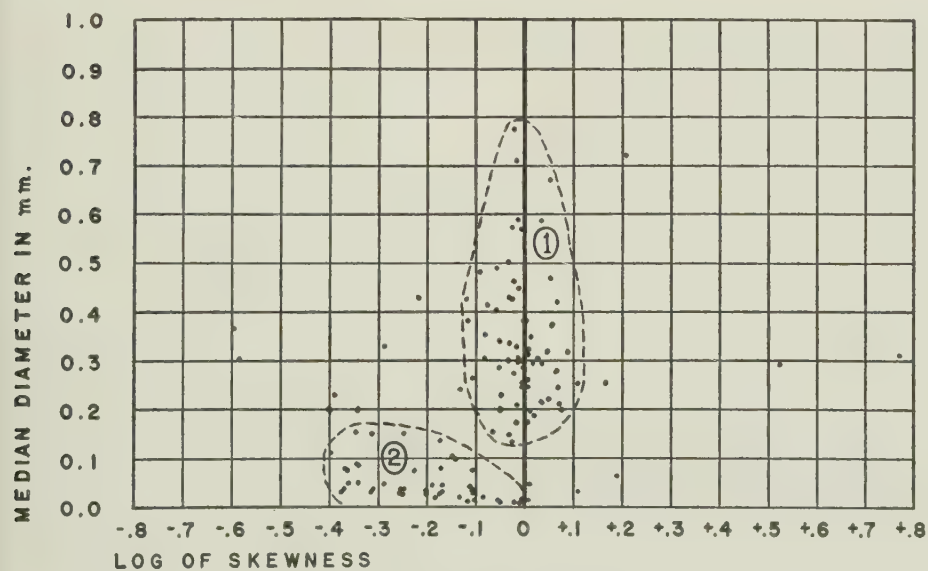


FIG. 4.—Graph of median diameter plotted against logarithm of skewness.

0.12, and being about equally distributed on either side of skewness log zero. A few of the coarser sediments are widely scattered on the graph. These are the same samples which have sorting values greater than 2.00 in figure 3. Practically all of the remaining samples fall into a group with median diameters less than 0.160 mm. and logs of skewness from zero to minus 0.40.

The deep hole in the bay north of Quicks Hole channel (fig. 2) contains sand having a median diameter of 0.254 mm. in its deepest part where the depth is 126 feet. No sediment finer than about 0.200 mm. median diameter was found in the depression, but in many places outside this area, in less than 60 feet of water, sediment of less than 0.061 mm. median diameter was found. Quicks Hole channel is floored with an erosion resisting pavement of coarse gravel and organic growth (mainly calcareous algae and hydrozoa) while the shoal extending northward from the west side of Quicks Hole to Lone Rock is composed of gravel and coarse sand with a large amount of shell material. Between Lone Rock shoal and the bottom of the 126-foot depression the sediment decreases in grain size but maintains its clean-washed, oxidized appearance and its high shell content. The strong tidal currents of Quicks Hole pouring into Buzzards Bay seem to be directly related to this distribution of sediment. It is not possible to assign the origin of the depression to scouring by the tidal current, but the current apparently is responsible for the non-accumulation of fine-grained sediment.

Some of the closed depressions in the submerged channels in the mouth of Buzzards Bay also contain coarse sediment. Sand with a median diameter of 0.262 mm. is present at a depth of 140 feet in one of these holes. The reason for this occurrence is less clear than in the depression adjacent to Quicks Hole. However, it seems probable that the islands and numerous gravel covered shoals in the mouth of the bay produce a concentration of tidal flow sufficient to cause ap-

preciable current velocity at the bottoms of some of the depressions.

MINERALOGICAL COMPOSITION

Nine samples were selected for mineralogical study. Six of these² were taken along a line crossing the bay at a right angle to its axis between Wilkes Ledge³ and Quicks Hole. The remaining three samples⁴ were taken on the sides of the deep hole north of Quicks Hole. The grade between 0.104 and 0.208 mm. was studied because all nine samples contained material in this range. No far-reaching conclusions can be drawn from the study of a single arbitrarily chosen grade, but the data indicate which minerals are present and permit certain generalizations to be made.

Quartz is the most abundant mineral in all of the samples. Orthoclase and plagioclase feldspars are second in abundance in most of the samples. The light fractions contain, besides the minerals just mentioned, a few Foraminifera, Ostracoda and fragments of Hydrozoa.

The heavy minerals identified in the samples are listed in table 2 with figures showing relative abundance. The most abundant heavy minerals are aragonite, opaque metallics, hornblende and muscovite. Brown tourmaline is present in small amounts in all the samples studied. The aragonite is organic in origin and represents fragments of animal tests. Biotite evidently is undergoing alteration from an original state in which its color is brown to a product which possesses a green color and is nearly isotropic in character. A few grains were observed which were partly brown and unaltered and partly green and nearly isotropic. Rare grains with a green color showing compound polarization were identified as glauconite, and, in the light of Galliher's work (1935), are believed to repre-

² Sample Nos. 163, 168, 170, 171, 173 and 175.

³ Position, 41° 30' 45'' N., 70° 54' 40'' W., shown in figure 2 as a gravel covered shoal.

⁴ Sample Nos. 143, 145 and 153.

sent the end product of alteration of the biotite. The opaque metallic minerals are largely magnetite, but include a small percentage of ilmenite and opaque brown constituents. The garnets are mainly salmon-colored, but a few colorless (blu-

inverse power function of the median diameter of the sample. These minerals make up only 3.8 per cent of the heavy fraction of the 0.104–0.208 mm. grade in a sample having a median diameter of 0.575 mm., whereas they constitute 84.9

TABLE 2. *Mineralogical composition of heavy fraction of 0.104–0.208 mm. grade, in nine samples of sediment from Buzzards Bay, Massachusetts**

Mineral	Sample number								
	163	168	170	171	173	175	143	145	153
	%	%	%	%	%	%	%	%	%
Aragonite	54.4	7.2	1.5	1.5	3.8	9.2	10.3	.9	11.9
Biotite (brown)	.8	—	4.4	5.1	3.8	4.5	1.0	6.7	—
(green)	1.6	4.1	14.8	20.1	16.8	5.3	3.4	1.7	2.8
Calcite	—	—	—	—	—	3.8	1.5	—	6.3
Chlorite	3.6	1.1	1.5	.7	.8	9.2	1.5	2.5	2.8
Enstatite	—	2.0	.7	—	.7	—	1.5	3.4	—
Epidote	3.2	—	7.4	.7	1.5	3.8	9.3	8.4	6.6
Ferrous metallics	13.9	44.4	4.4	.7	.8	6.9	17.1	25.1	27.9
Garnet	2.4	7.2	.7	—	—	.8	2.5	3.4	4.9
Glauconite	—	—	—	—	—	2.3	2.5	—	—
Hornblende	6.7	17.5	5.9	1.5	2.3	16.0	4.4	11.8	5.6
Kyanite	—	1.1	.7	—	—	—	—	—	.7
Muscovite	6.4	4.1	40.6	57.3	53.4	5.3	6.9	5.9	5.9
Olivine	—	—	—	—	—	—	1.0	—	—
Sillimanite	.4	—	—	—	.7	5.3	3.4	.9	2.4
Titanite	.4	1.0	—	.7	.8	—	1.5	1.7	.4
Topaz	1.6	—	—	—	—	.8	.5	—	1.0
Tourmaline	1.2	1.0	2.2	.7	.8	2.3	4.4	5.0	3.5
Zircon	.8	3.0	—	.7	—	—	—	2.5	1.4
Zoisite	—	—	—	—	—	—	.5	—	.4
Altered	2.0	5.1	9.5	2.3	9.2	12.2	11.2	4.1	7.7
Miscellaneous	.8	1.1	5.9	8.1	4.6	12.2	15.6	16.0	7.7
Heavy minerals in grade; % by weight	14.0	16.7	1.9	3.5	5.8	1.7	3.1	3.5	3.4
Depth of water in feet	20	39	63	58	56	33	62	80	52
Median diame- ter in mm.	1.156	.575	.061	.061	.061	.144	.262	.198	.245

* Refer to table 1 for location.

ish-colored in piperine) grains of the mineral occur. The zircons are bluish-purple in color, and most of them are well-defined crystals. Altered minerals include various light-colored opaque or translucent grains.

The amount of micaceous minerals, muscovite, biotite and altered biotite, present in the heavy fractions of the one size-grade studied, varies roughly as an

per cent of the corresponding part of a sample having a median diameter of 0.050 mm. The great abundance of the micaceous minerals in the coarser fractions of the fine-grained, mid-bay sediments can be explained on the basis of their low hydraulic values (or small equivalent diameters) relative to those of the more spherical grains occurring in the same sediment.

Localities favorable to the growth of shell-secreting organisms have bottom sediments containing much shell material. When shells occur in a situation where wave action is of importance, they are broken and much of the carbonate material is incorporated as sedimentary grains and finds a place in the regular size distribution of the sands. In the deeper

TABLE 3. *Acid-soluble material in sample no. 142, * Buzzards Bay, Massachusetts*

Depth in core	Acid-soluble material
<i>Cm.</i>	<i>Per cent</i>
0- 5	3.24
5-10	3.13
10-15	2.92
15-20	2.37
20-25	2.32

* Refer to table 1 for location.

waters of the bay where fine-grained sediment is accumulating, the shells are not mechanically broken and they occur as erratic particles of relatively large size and do not form a part of the regular size-distribution curves.

In order to determine the variation in amount of acid-soluble material with depth in the sediment, a core sample (no. 142) of the fine-grained deposit in the south-central part of the bay was divided into sections of 5 cm. each, and a representative part of each section was treated with acid. Table 3 gives the results of this study. There is a small but continuous decrease in amount of acid-soluble material from top to bottom of the core. Stratification of this deposit is indicated partly by variation in quantity of shells. The recognizable layers have an average thickness of about 1.5 cm., but, as described below, these layers may include one or several years' contribution of sediment. Thus the 5 cm. sections may represent the accumulations of several years. The decrease in amount of carbonate with depth in the core must be due either to a long time trend in amount of car-

bonate deposited or to a slow solution of the carbonate. The shells in the deeper layers of several core samples examined are thin, lacking in lustre, and are structurally weakened thus showing the effects of solution.

ORGANIC CONTENT

The organic content of the fine-grained sediments of the bay averages about 2 per cent, as determined in analyses of 20 samples by Seiwell. The fine-grained material with this organic content possesses a black color when wet and a dark grey color when dry. In order to determine whether such a deposit might be a source sediment of petroleum, a calculation was made of the probable oil yield of the deposit.

Using Trask's data on oil yield of organic sediments (1932, p. 40), it may be calculated that one cubic foot of the fine-grained Buzzards Bay sediment could yield 0.07 cubic foot of oil. The area covered by the fine-grained sediment is roughly 100 square miles. A layer of sediment 10 feet thick in this area would have a volume of 28 billion cubic feet. At the rate of 0.07 cubic foot of oil per cubic foot of sediment, this deposit would produce 1,960,000,000 cubic feet or 350 million barrels of oil. It is thus seen that the fine-grained sediment of Buzzards Bay might be a source sediment of petroleum at some time in the future.

STRATIFICATION

Distinct stratification shown by variations in grain size or in shell content was observed in many of the core samples of fine-grained sediment. Freshly collected cores were laid horizontally on a table and sliced longitudinally by pushing a knife through them in a direction normal to the length of the core. Thin layers of fine sand were detected by prodding the exposed faces with a needle. Shells were located by carefully separating one of the halves of each core with a needle.

The layers observed were approximately 1 to 2 cm. thick. It is impossible

to say whether these layers represent annual deposits of sediment. An estimate can be made of the maximum thickness annual layers could have in the bay, as follows: the probable maximum depth that the bay could have had in any considerable area in its south-central part is 100 feet, a figure obtained by comparison of the topography of the bay with that of the adjacent Vineyard Sound and ocean floor. If the original depth were 100 feet, and the average present depth in the area of fine-grained sediment is taken as 50 feet, then a deposit of sediment 50 feet thick has been laid down. The minimum length of time during which water surface has been at or near its present level is taken as 10,000 years, the approximate period elapsed since withdrawal of the glacial ice from the area. Assuming that 50 feet of sediment were laid down in 10,000 years, the average thickness of one year's deposit is 1.5 mm. If compaction is taken into account, the surface layers of the deposit would have a thickness somewhat greater than this. Considering the grain size of the deposit, it is estimated that the porosity in its lower part would be about 35 per cent and the porosity in the upper 25 cm. would be about 65 per cent. The layers in the upper 25 cm. would have a thickness of about 2.3 mm.

The average thickness of the layers observed in the core samples is 1.5 cm., about 6.5 times as great as the calculated maximum possible thickness of annual layers. The discrepancy may be explained in two ways. (1) The thickness of observed layers may represent more than one year's deposit. This is possible if the coarser grains and the concentrates of shells observed in the cores represent unusual conditions occurring only once in several years. (2) The rate of accumulation of sediment may be greater at present than during most of the life of the bay. This is possible because the rate of erosion of the watershed probably has been increased materially by cutting of forests and cultivation of the soil.

INTERPRETATIONS

Sources of sedimentary material.—Because of its abundance and unconsolidated character, glacial drift is by far the most important source of sedimentary material. The constituents of the drift were derived from the land to the northwest, as shown by the fact that Dedham granodiorite is the most common type of rock present. In texture the drift is coarse; grains in the sand sizes are most abundant and little silt or clay is present. The Dedham granodiorite of the northwestern shore is comparatively very resistant to erosion; therefore, the amount of material it contributes directly is small. The mineralogy of the bay sediments is related to that of the granodiorite and indicates an ultimate origin in that rock mass.

A considerable amount of calcium carbonate is contributed to the sediments of the bay by shell-secreting organisms. Whole shells and shell fragments occur in abundance at the surface of the deposits, but solution of the carbonates apparently is taking place in the deposit so that they do not represent a permanent contribution of great importance.

Wave action.—The storm waves and swells of the open ocean reach only a short distance into the bay, because of the protection afforded by the islands and shoals at its mouth, but waves generated within the bay attain a considerable size. The more exposed shores of the bay show abundant evidence of wave attack in their low cliffs and boulder-strewn beaches. It is difficult to judge the intensity of wave action on the bottom of the bay. Coarse sediment occurs on topographic highs in as much as 40 feet of water. This coarse concentrate may have developed largely during a time of lowered sea level and since that time have been kept free of fine sediment and organic matter by gentle bottom currents. However, wave action at a depth of 40 feet in a body of water the size of Buzzards Bay should be capable of producing

the concentrate observed, since Kindle (1925) reports the destruction by wave action of a staunch vessel and the removal of its 75 tons of coal while sunk in 65 feet of water in Lake Ontario.

Tidal currents.—In the channels between the islands of the Elizabeth chain, the tidal currents have maximum velocities of 4 to 6 knots at the surface, and currents near the bottom in the center of the bay have maximum velocities of 0.5 knot.⁵ Coarse sediment is transported in the tidal channels between the islands, but only fine silt and organic matter are carried into the central part of the bay.

Ice rafting.—During the colder winters a large amount of ice forms in the bay and in the adjacent sound. It is swept through the tidal channels and ground against the shores by the tidal currents. Some sedimentary material may be transported by the ice and rare particles of coarse sand and gravel occurring in the

fine-grained sediments may have been contributed in this manner.

Change in topography of the bay.—The bay shores, subject to the most violent erosive action, have undergone little change in shape. Headlands and island shores have been cut back several feet. Many indentations have been reduced in curvature and some have been nearly closed off by deposition of sand and gravel, but the net change in configuration of the shore lines has been small. The presence of abundant boulders in the glacial drift results in the formation of a boulder pavement on the beaches that is very resistant to erosion.

The bottom topography has been rendered more gentle by erosion of the shoals and deposition in most of the hollows, but the shoal areas, like the beaches, are protected by coarse concentrates and, therefore, waste slowly. The greatest change in topography seems to have taken place in the central part of the bay where accumulation of fine-grained sediment has produced a gently sloping floor.

REFERENCES

- GALLIHER, E. W., 1935, Geology of glauconite: *Amer. Assoc. Petroleum Geologists Bull.*, vol. 19, pp. 1569-1601.
- HOUGH, J. L., 1939, Chapter on bottom sampling apparatus: *Symposium on Recent Marine Sediments*, committee on sedimentation, National Research Council, Gulf Publishing Co., Houston, Tex.
- KINDLE, E. M., 1925, Bottom deposits of Lake Ontario: *Royal Soc. Canada, Proc. and Trans.*, 3rd ser., vol. 19, pp. 29-30.
- KRUMBEIN, W. C., 1932, A history of the principles and methods of mechanical analysis: *Jour. Sed. Pet.*, vol. 2, p. 111.
- OTTO, G. H., 1933, Comparative tests of several methods of sampling heavy mineral concentrates: *Jour. Sed. Pet.*, vol. 3, p. 32.
- STETSON, H. C., and UPSON, J. E., 1937, Bottom deposits of the Ross Sea: *Jour. Sed. Pet.*, vol. 7, p. 57.
- TRASK, P. D., 1932, *Origin and Environment of Source Sediments of Petroleum*: Gulf Refining Co., Houston, Tex., pp. 70-75.
- VEATCH, A. C., 1906, Outlines of the geology of Long Island: *U. S. Geol. Survey, Prof. Paper*, 44, pp. 26-32.
- WENTWORTH, C. K., 1926, Methods of mechanical analysis of sediments: *Univ. of Iowa Studies*, vol. XI, no. 11, pp. 20-35.

SEDIMENTS OF CAPE COD BAY,
MASSACHUSETTS

BY

J. L. HOUGH

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SEDIMENTS OF CAPE COD BAY, MASSACHUSETTS

J. L. HOUGH*

University of Chicago, Chicago, Illinois

ABSTRACT

Cape Cod Bay, lying on the Massachusetts coast partly enclosed by Cape Cod, is in a glaciated region of low relief. Coarse sediments generally occur in areas exposed to wave and current action as in shallow water near shore or on shoals, and in the deep channel north of the tip of Cape Cod, which is swept by tidal currents. Fine sediments are restricted to the deeper water in the central portion of the Bay, and to the small, well-protected embayments of the shores.

Most of the sediments are well sorted as compared with other shallow-water marine sediments. Within the Bay, the coarser materials generally have the highest degree of sorting while the finer sediments invariably are more poorly sorted. Fine-grained materials contain a small amount of organic matter and generally are stratified in layers 1 to 2 cm. thick. Sphericity of the pebbles varies but little and in a random manner, but roundness decreases with increasing depth of water.

A previously described hard bottom zone in Massachusetts Bay was traced into Cape Cod Bay. This hard bottom consists of a concentrate of pebbles produced by wave and current erosion of glacial drift on the bottom under present conditions.

The sediments studied are similar to those in Buzzards Bay, Massachusetts Bay and San Francisco Bay, but they differ somewhat from those of the continental shelf, a more exposed environment, and from those of Barataria Bay, a more protected environment.

INTRODUCTION

This study is a part of the program of the Woods Hole Oceanographic Institution relating to the investigation of sediments of the continental shelf and coastal waters of the eastern United States. Field operations were carried on from that institution's base at Woods Hole, Massachusetts, during the Summer of 1935. Laboratory analyses of the sediments were made in the Woods Hole laboratory and in the sedimentation laboratory of the University of Chicago.

The objectives of the study were to collect quantitative data on modern sediments occurring in an environment whose characters are known, to describe the relationships between the sediments and their environment, and to discuss the geological significance of these relationships.

THE PHYSICAL ENVIRONMENT

Cape Cod Bay (fig. 1) lies inside the

arm of Cape Cod, on the Massachusetts coast. It is one of the larger and deeper embayments of the coastal waters of the eastern United States.

Geology.—The bedrock of the mainland of Massachusetts, west of Cape Cod Bay, is Dedham granodiorite, a part of a shield of igneous and metamorphic rocks which constitutes the bulk of the New England Lowland. A few deep well borings show that the surface of the crystalline mass extends beneath Cape Cod to the east and south. The bedrock is at or near the surface along the western shore of the Bay north of Plymouth. The other shores of the Bay are formed by thick deposits of glacial drift.

The general shape of the bay was determined largely by glacial deposition on an erosional surface of low relief. The shores of Cape Cod Bay consist of frontal and interlobate deposits which are predominantly outwash material (fig. 2). Since glacial times the bay shores, subject to the most violent erosive action, have undergone relatively little change in shape. Headlands and island shores

* Contribution no. 184, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

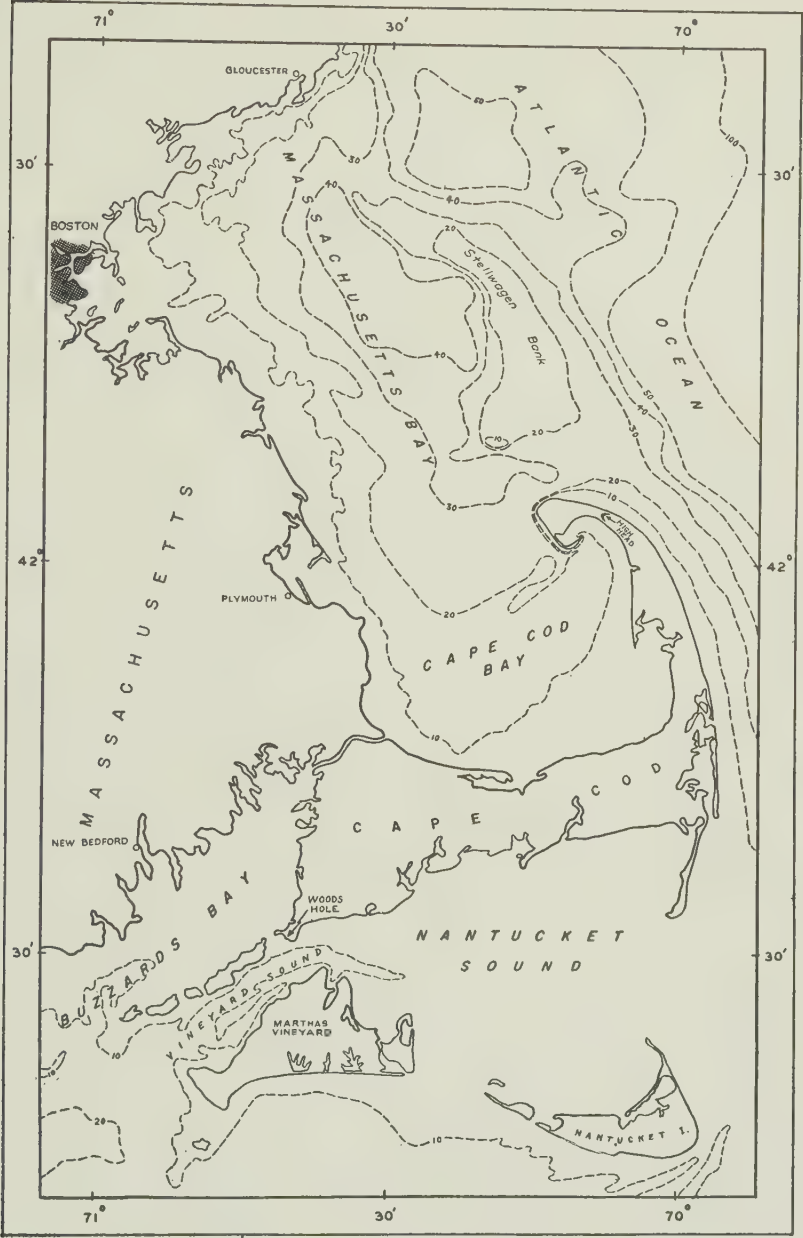


FIG. 1.—Index map showing location of Cape Cod Bay, Massachusetts.

have been cut back considerable distances and many indentations have been reduced in curvature and some have been nearly closed off by deposition of sand and gravel, but the net change in con-

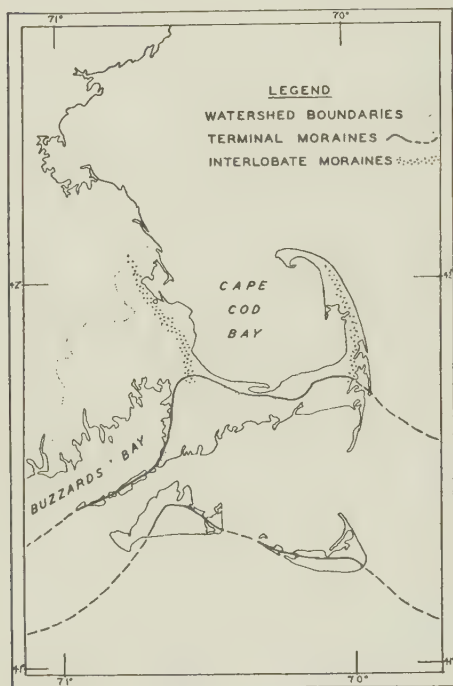


FIG. 2.—Watersheds of Cape Cod Bay and Buzzards Bay, and glacial moraines of the region. (After Woodworth and Wigglesworth.)

figuration of the shore lines has been small. The greatest change in shoreline has been the formation of the hooked northern end of Cape Cod, north of High Head.

When the glacial ice disappeared from southern New England in late Pleistocene time, the sea was perhaps as much as 200 feet below its present level. The bottom of Cape Cod Bay must, therefore, have been exposed to subaerial processes for at least a short time.

Hydrography.—Cape Cod Bay is roughly circular with a diameter of about 22 miles. Its average depth is more than 100 feet and its maximum depth is 220

feet. The bottom topography is shown in figure 3. Considered in detail, the topography is rough and reflects the effects of glaciation. Two well-defined ridges extend across the bay in a northeasterly direction. One of these lies on a line between the Cape Cod Ship Canal and Provincetown, and the other is on a line between Barnstable Harbor and Wellfleet. These may be recessional moraines.

Between the tip of Cape Cod and Stellwagen Bank, to the north (fig. 1), is a channel whose floor reaches a depth of 198 feet. The top of Stellwagen Bank, in its southern part, has an average depth of about 80 feet but a small area on its southwestern corner, opposite Race Point (the northwestern tip of the Cape) reaches a depth of only 57 feet.

Stellwagen Bank, like the arm of the Cape with which it is aligned, is generally considered as an interlobate glacial deposit. After the continental ice sheet disappeared from this area, Massachusetts Bay and a small part of the Cape Cod Bay area may have been occupied by a much-restricted body of water which was nearly or entirely separated from the Atlantic Ocean by the Bank and the Cape. As sea level rose to within 80 feet of its present elevation, two connections with the ocean existed, one to the north of Stellwagen Bank and the other between the Bank and Cape Cod. With continued rise of the sea, Massachusetts Bay was completely connected with the ocean but Cape Cod Bay remained partially enclosed.

The deepest point in Cape Cod Bay, 220 feet, lies at the inner end of the channel between the Cape and Stellwagen Bank. An area comprising several square miles extending from this point toward Plymouth has a depth of more than 160 feet. A well-defined shelf is present in the northwestern part of the bay, as shown by the contours of figure 3. The greater part of the Bay, to the south, has a regularly-sloping bottom with the exception of the two ridges already described.

The bottom configuration of the bay has been made generally more smooth



through slight erosion of the higher parts and through deposition of material derived principally from erosion of the shores and above-water portions of the area. The shoal areas, like the beaches on salient points, are protected by coarse concentrates and, therefore, waste slowly. The greatest change in bottom topography has taken place in the deeper, central portion of the bay where accumulation of fine-grained sediment has produced a gently-sloping floor.

The prevailing winds of the region blow from the southeast, but the storm winds generally are northeasterly. Waves generated by the northeasterly storms reach the western shore of Cape Cod Bay although they are damped somewhat by Stellwagen Bank and by dissipation of energy after they pass Cape Cod. Waves generated within the Bay attain considerable size and are important factors in shore erosion. Wave erosion of salient points of the shores, where they are composed of unconsolidated material, has removed a considerable volume of material. Shore erosion on exposed points is resisted, however, by boulder pavements formed by concentration of the abundant coarse particles of the glacial drift.

Wave action on the bottom of the Bay is effective in removing fine material at considerable depths. Outside the areas where bottom currents are the most probable agents of erosion, accumulations of gravel suggest that wave erosion occurs at depths as great as 140 feet. Above the 80-foot contour in the northwestern part of the Bay, a predominance of gravel indicates that wave action is of importance. This area will be discussed in greater detail below.

Littoral currents, generated by the wind and acting in conjunction with waves, play an important role in distribution of sediments. Many bars and spits have been constructed of material derived from headlands and the adjacent bottom.

Bottom currents have not been investigated very thoroughly, but something

of their location and strength may be inferred from available information on surface currents and by analogy with other bodies of water. Strong surface currents exist north of the tip of Cape Cod. This fact, and the occurrence of coarse sediment on the bottom in nearly 200 feet of water, indicate that bottom currents are strong also. The vertical range of the tide is 13.6 feet at Plymouth and similar ranges occur at several other points in the Bay. This large range of the tide indicates that a considerable volume of water is moved by tidal action and that tidal currents must be of importance at many localities in the Bay.

Hydrology.—Because of the broad connection between Cape Cod Bay and the ocean, the volume of tidal flow, and the small volume of inflow of fresh water from the land, the salinity of the Bay waters is comparable to that in the adjacent ocean. The oxygen content of the water in the Bay is probably about the same as in the ocean, except where local conditions such as proximity to muds with a high organic content may modify the water adjacent to the bottom.

The average annual precipitation of the area is about 40 inches. The area of land surface draining into the Bay (fig. 2) is comparatively small, comprising 224 square miles, or an area equal to only 36 per cent of the surface area of the Bay, which is 618 square miles.

The soils of the area draining to the Bay generally are sandy and permit rapid infiltration of a large percentage of the rainfall. Slopes in the land area are gentle and the maximum elevation in the watershed is about 325 feet. This is at Manomet Hill near Manomet Point on the western shore. No other point in the area rises above 300 feet. There are numerous lakes and marshes. Drainage is poorly developed and most of the streams flow into estuaries or small, protected embayments rather than directly into the Bay.

As a consequence of the hydrologic conditions described, the quantity of water flowing into Cape Cod Bay from

the land surface is small and the amount of sediment which this water contributes to the open bay must be very small.

METHODS OF STUDY

Field Methods.—Bottom samples were collected from the 40-foot power boat "Asterias," owned by the Woods Hole Oceanographic Institution. Core samples of the fine-grained bottom sediment were taken with a Trask coring tube and samples of coarser material were taken with the Stetson-Iselin sampler and with the Fish Hawk type clamshell snapper (Hough, 1939). The points sampled were located on lines crossing the Bay in various directions, usually between buoys and lighthouses. The usual distance between samples on a line was one mile. Core samples were preserved for laboratory study by wrapping them in sheets of newspaper, while incoherent coarse materials were placed in glass jars.

Beach and cliff samples were collected from the shores of Cape Cod Bay by hand, and each sample is a composite made up of four samples collected within a small area at each locality.¹

In addition to the beach samples collected for mechanical analysis, two samples of beach pebbles were collected for shape studies. Beach samples A and B (table 3) were collected from the western edge of the tip of Cape Cod between Race Point and Wood End. Sample A consists of all the particles larger than 4 mm. in diameter over an area about one meter square marked out just above the high tide line on the beach (elevation above mean sea level about 10 feet). Sample B was taken in a similar manner just below the high tide line (elevation about 8 feet).

The beach on the southern shore of the bay between the ship canal and Barnstable Harbor was covered with sand during most of the summer of 1935, but during September, when the beach samples

were collected, only pebbles could be found on this shore. Storms in the early part of September had removed the sand.

Laboratory Methods.—Laboratory analyses for mechanical composition were made by the pipette and sieving methods (Krumbein and Pettijohn, 1938).

Shape studies followed Wadell's method (Krumbein and Pettijohn, 1938, pp. 295-299) with certain modifications. Following Wadell, the roundness value is defined as the average radius of curvature of all the corners of a particle. Sphericity is defined as the ratio between the diameter of a circle with an area equal to that of the projection of a plane of the particle to the diameter of the smallest circumscribing circle.

The projection images used for these were obtained by photographing or photostating the pebbles, using appropriate lens combinations to achieve a standard size of about 7 cm. The pebbles were first separated into groups of approximately equal size and placed in their most stable positions on a background of contrasting color.

Statistical Analysis.—The laboratory data were analyzed by the methods described by Trask (1932), involving the use of first quartile, median and third quartile diameters and the calculation of sorting factor ($So. = \sqrt{Q1/Q3}$) and Skewness ($Sk. = Q1 \times Q3/M^2$). The arithmetic means of the sphericity and roundness distributions were calculated by the usual statistical methods.

THE SEDIMENTS OF CAPE COD BAY

General Distribution.—The bottom sediments range from black, fine silts to gravels and boulders. In Cape Cod Bay proper, outside of the smaller embayments such as Wellfleet Harbor and Duxbury Bay, there is a general relationship between size of sediment particles and depth of water, the finer material occurring in the deeper water. The sediments are classified arbitrarily into three types as follows:

I, gravel and coarse sand (median

¹ Four samples were taken to reduce sampling error (Krumbein, 1934). The localities sampled are shown in figure 3.

diameter greater than 0.500 mm.); II, sands of medium and fine grade (median diameter 0.500 to 0.061 mm.); and III, silts and clays (median diameter less than 0.061 mm.).

The areal distribution of these types in Cape Cod Bay is shown in figure 3. In the northwestern part of the Bay, the coarse sediment of type one predominates from the shore outward to a depth of about 80 feet, 5 miles from shore. Southward to a point midway between Plymouth Bay and the Cape Cod Ship Canal this type extends to the 80-foot contour in a narrowing zone which is only 2 miles wide at the southernmost point described. From here southeastward around the southern end of the bay, type one gives way to the intermediate sediment sizes of type two, except in the shallower water, principally above 40 feet. A few areas of type one extend down to the 60-foot contour off Barnstable Harbor and Billingsgate Shoal.

The fine sediment of type three occurs in the central part of the Bay and extends up to the 140-foot contour in the northwestern part, up to about 90 feet in the southern part and above 80 feet in the eastern part along the western slope of the Cape. In the deep water between the northern tip of Cape Cod and Stell-

wagen Bank, type three sediment is displaced by sands of sediment type two.

On the beaches, sand is by far the most abundant material, though pebbles are present on every shore. During a storm practically all grains of sand size may be removed from the beach, but in a short time sand reappears. Characteristics of the beach sands are discussed in a later section of the report.

Analyses.—The size analyses of the Cape Cod Bay sediments constitute too lengthy a record to be published here, but they may be consulted in the library of the University of Chicago.² For an understanding of the study as it is developed in the present paper, this material is not needed since the statistical constants of size distribution are given in tables 1 and 2. Data on properties other than size are given in the following pages.

Statistical Summary of Data.—Statistical constants of the size distribution are given in tables 1 and 2, average sphericity and roundness values are given in table 3, and lithological composition of pebbles is given in table 4. A discussion of these data follows:

² Hough, J. L., The sediments of Buzzards Bay and Cape Cod Bay, Massachusetts, Doctor's dissertation, December 1940.

TABLE 1. *Statistical Constants of Bottom Sediments of Cape Cod Bay, Massachusetts*

Sample No.	Latitude	Longitude	Depth in Feet	Statistical Constants					Remarks
				Diameters in mm.			So.	Log Sk.	
				Q1	Med.	Q3			
1	42°05'36"	70°36'18"	30	1.130	1.790	3.190	1.68	+ .048	Shells
2	05'48"	34'54"	82	.162	.192	.231	1.19	+ .005	
3	06'00"	33'42"	98						
4	06'18"	32'24"	110	.288	.459	1.350	2.16	+ .265	
5	06'30"	31'12"	120	.290	.369	.494	1.30	+ .022	
6	06'48"	29'54"	152	.308	.361	.448	1.45	+ .025	
7	07'24"	27'18"	174	.498	.815	1.392	1.67	+ .017	
8	07'54"	24'42"	180	.021	.051	.086	2.02	— .157	
9	08'24"	22'06"	188	.0905	.122	.179	1.41	+ .033	
10	09'00"	19'30"	60	.412	.560	.772	1.37	— .006	
11	09'30"	17'00"	75	.325	.423	.585	1.34	— .024	
12	08'36"	16'45"	150	.164	.234	.378	1.52	+ .054	
13	07'36"	16'30"	185	.280	.359	.505	1.34	+ .041	
14	06'36"	16'15"	190	.152	.187	.241	1.26	— .020	
15	05'36"	16'00"	175	.172	.244	.344	1.42	— .003	

TABLE 1. *Continued*

Sample No.	Latitude	Longitude	Depth in Feet	Statistical Constants					Remarks
				Diameters in mm.			So.	Log Sk.	
				Q1	Med.	Q3			
16	42°04'39"	70°15'45"	180	.189	.250	.345	1.35	+ .019	Silty clay
17	03'40"	15'30"	140	.224	.279	.345	1.24	- .003	
18	02'42"	15'06"	150	.163	.195	.239	1.17	- .011	
19	00'00"	35'06"	60	—	< .061	—	—	—	
20	00'23"	33'40"	93	.121	.164	.334	1.66	+ .176	
21	00'45"	32'11"	108	.114	.147	.226	1.41	+ .077	
22	01'07"	30'42"	120	.600	.778	1.020	1.31	+ .005	
23	01'29"	29'07"	132	.160	.210	.281	1.32	+ .008	(1st trial) one pebble (2nd trial)
24	01'41"	28'26"	135	.464	3.250	18.050	1.97	- .003	
25A	01'55"	27'07"	145	—	—	—	—	—	
25	01'55"	27'07"	145	.098	.163	.341	1.87	+ .099	
26	02'11"	25'49"	148	.0363	.062	.085	1.53	- .095	
27	02'42"	23'15"	170	.0318	.0365	.0561	2.22	- .236	
28	03'12"	20'36"	180	.0097	.0280	.0434	2.05	- .269	
29	03'42"	18'01"	180	.010	.0341	.060	2.45	- .286	Fine sand
30	41°54'54"	70°30'30"	65	.096	.125	.170	1.33	+ .018	
31	55'52"	30'12"	95	.197	.558	8.450	2.78	- .272	
32	56'52"	29'54"	99	.096	.188	.346	1.90	- .024	
33	57'53"	29'36"	108	1.360	4.050	7.900	2.40	- .184	
34	58'53"	29'18"	115	.129	.212	.317	1.57	- .041	
35	59'53"	29'00"	125	.163	.236	.340	1.69	- .004	
36	42°00'53"	28'42"	135	.390	5.500	21.250	7.39	- .562	Fine sand
37	41°55'06"	30'30"	66	.116	.138	.180	1.24	+ .039	
38	55'23"	29'38"	25	—	> .061	—	—	—	
39	55'43"	28'13"	98	.108	.140	.196	1.38	+ .034	
40	56'07"	26'48"	100	—	> .061	—	—	—	
41	56'38"	25'26"	125	—	< .061	—	—	—	
42	56'58"	24'05"	125	—	< .061	—	—	—	
43	57'23"	22'42"	124	—	< .061	—	—	—	Silt
44	57'48"	21'20"	134	—	< .061	—	—	—	Silt
45	58'13"	19'55"	134	—	< .061	—	—	—	Silt
46	58'40"	18'34"	136	—	< .061	—	—	—	Silt
47	59'02"	17'11"	130	—	< .061	—	—	—	Silt
48	59'31"	15'53"	130	—	< .061	—	—	—	Silt
49	42°00'04"	14'35"	125	—	< .061	—	—	—	Silt
50	00'43"	13'34"	125	.121	.162	.202	1.29	- .032	Med. sand Fine sand Coarse sand
51	01'23"	12'58"	150	.112	.139	.178	1.26	- .013	
52	00'58"	27'25"	148	.123	.253	.356	1.70	- .164	
53	00'17"	26'25"	145	—	> .061	—	—	—	
54	41°59'36"	25'25"	145	—	> .061	—	—	—	
55	58'54"	24'25"	145	—	> .061	—	—	—	
56	58'12"	23'25"	138	—	< .061	—	—	—	
57	56'52"	21'25"	130	—	< .061	—	—	—	Silt
58	56'11"	20'25"	124	—	< .061	—	—	—	Fine silt
59	55'29"	19'25"	108	—	< .061	—	—	—	Clay
60	54'47"	18'25"	115	—	< .061	—	—	—	Clay
61	53'23"	16'25"	106	—	< .061	—	—	—	Clay
62	52'01"	14'23"	90	—	> .061	—	—	—	Fine sand, silt
63	50'37"	12'23"	50	.462	.640	.990	1.46	+ .057	
64	49'55"	11'23"	37	.340	.650	.990	1.71	- .099	
65	49'13"	10'19"	20	.440	.550	.685	1.25	- .002	
66	48'19"	09'29"	32	.156	.184	.221	1.19	+ .008	
67	47'38"	08'41"	26	.159	.187	.235	1.22	+ .029	
68	46'53"	07'49"	24	.188	.244	.311	1.28	- .007	
69	46'30"	07'41"	18	.452	.722	.900	1.41	- .107	

TABLE 1. *Continued*

Sample No.	Latitude	Longitude	Depth in Feet	Statistical Constants					Log Sk.	Remarks
				Diameters in mm.			So.			
				Q1	Med.	Q3				
70	41°54'48"	70°29'01"	102	—	> .061	—	—	—	—	Fine sand
71	54'24"	27'44"	94	—	—	—	—	—	—	Fine sand, silt
72	54'01"	26'25"	98	—	—	—	—	—	—	Fine sand, silt
73	53'39"	25'07"	100	—	< .061	—	—	—	—	Silt
74	53'15"	23'52"	98	—	—	—	—	—	—	Fine sand, silt
75	53'11"	23'35"	98	—	—	—	—	—	—	Fine sand, silt
76	52'48"	22'17"	102	—	< .061	—	—	—	—	Silt
77	52'35"	21'37"	98	—	< .061	—	—	—	—	Silt
78	52'25"	20'59"	96	—	< .061	—	—	—	—	Silt
79	52'01"	19'38"	96	—	> .061	—	—	—	—	Fine sand
80	51'36"	18'18"	93	—	> .061	—	—	—	—	Fine sand
81	51'13"	16'59"	92	—	> .061	—	—	—	—	Med. sand
82	50'50"	15'40"	84	—	> .061	—	—	—	—	Med. fine sand
83	47'46"	28'23"	48	.297	.346	.427	1.20	+ .025		
84	48'54"	27'45"	64	.289	.348	.430	1.22	+ .008		
85	49'48"	26'48"	78	—	< .061	—	—	—	—	Fine silt, clay
86	50'28"	25'55"	82	.041	.073	.118	1.70	— .042		
87	51'12"	24'59"	85	—	> .061	—	—	—	—	Med. sand
88	51'55"	24'04"	85	.041	.071	.110	1.64	— .047		
89	54'02"	21'18"	105	—	< .061	—	—	—	—	Silt
90	54'46"	20'24"	105	—	< .061	—	—	—	—	Clay
91	56'13"	18'35"	85	.225	.840	4.450	1.41	+ .152		
92	57'01"	17'44"	115	—	< .061	—	—	—	—	Clay
93	57'47"	16'56"	135	—	< .061	—	—	—	—	Clay
94	58'40"	16'07"	120	—	< .061	—	—	—	—	Clay
95	49'20"	26'26"	80	—	> .061	—	—	—	—	Fine sand
96	49'47"	25'12"	84	—	> .061	—	—	—	—	Med. sand
97	50'14"	23'59"	80	—	> .061	—	—	—	—	Med. sand
98	50'43"	22'46"	88	.045	.084	.129	1.69	— .085		
99	49'42"	28'58"	61	.037	.069	.103	1.67	— .095		
100	48'53"	26'23"	82	—	> .061	—	—	—	—	Fine sand
101	48'55"	25'01"	82	—	> .061	—	—	—	—	Fine sand
102	48'56"	23'43"	76	.208	.275	.361	1.32	— .002		
103	48'58"	22'28"	88	.044	.076	.101	1.52	— .114		
104	49'00"	21'07"	82	—	> .061	—	—	—	—	Fine sand
105	49'02"	19'47"	84	.042	.084	.110	1.62	— .183		
106	49'05"	18'28"	79	—	> .061	—	—	—	—	Med. sand
107	49'06"	17'10"	75	.089	.105	.152	1.31	+ .090		
108	49'08"	15'49"	65	.091	.108	.131	1.20	+ .009		
109	49'10"	14'26"	59	.116	.140	.197	1.30	+ .066		
110	49'11"	13'07"	50	.500	.720	.950	1.38	— .038		
111	49'13"	11'49"	29	.423	.599	.810	1.38	— .019		
112	45'06"	23'00"	55	.089	.102	.113	1.13	— .015		
113	45'59"	22'17"	66	.091	.110	.146	1.27	+ .041		
114	46'48"	21'40"	74	.115	.139	.158	1.17	— .029		
115	47'44"	20'59"	80	.064	.095	.110	1.31	— .106		
116	46'11"	15'44"	45	.431	.920	1.780	2.03	— .043		
117	47'07"	16'00"	46	.440	.641	1.700	1.97	+ .260		
118	48'05"	16'18"	60	.204	.260	.335	1.28	+ .003		
119	52'03"	13'00"	84	—	> .061	—	—	—	—	Fine sand
120	53'04"	12'47"	95	—	> .061	—	—	—	—	Fine sand
121	54'01"	12'32"	100	—	< .061	—	—	—	—	Silt and clay
122	55'00"	12'19"	105	—	< .061	—	—	—	—	Silt and clay
123	55'59"	12'02"	105	—	< .061	—	—	—	—	Silt and clay
124	56'59"	11'47"	100	—	< .061	—	—	—	—	Silt and clay
125	57'58"	11'34"	110	—	< .061	—	—	—	—	Silt and clay

TABLE 1. *Continued*

Sam- ple No.	Latitude	Longitude	Depth in Feet	Statistical Constants					Remarks
				Diameters in mm.			So.	Log Sk.	
				Q1	Med.	Q3			
126	41°58'56"	70°11'19"	114	—	< .061	—	—	—	Fine sand, silt
127	59'56"	11'06"	115	—	< .061	—	—	—	Fine sand, silt
128	42°00'56"	10'54"	120	—	< .061	—	—	—	Fine sand, silt
129	41°45'36"	14'45"	35	.302	.465	.740	1.57	+ .014	
130	46'23"	13'54"	40	—	> .061	—	—	—	Pebbles, sand, shells
131	47'06"	13'00"	37	.183	.249	.318	1.32	— .026	
132	47'47"	12'06"	35	.315	.592	.892	1.68	— .095	
133	48'31"	11'12"	40	.396	.498	.596	1.23	— .022	
134	50'00"	09'27"	12	.432	.554	.695	1.27	— .003	
135	50'41"	08'36"	10	.362	.465	.607	1.29	+ .009	
136	51'36"	07'48"	9	.374	.487	.624	1.29	— .007	
137	52'27"	07'00"	7	.495	.719	.864	1.32	— .083	
138	53'14"	06'11"	7	.325	.509	.671	1.43	— .076	
139	53'53"	07'03"	28	.950	1.225	1.700	1.34	— .030	
140	54'32"	07'55"	50	.518	.747	1.197	1.52	+ .046	
141	55'11"	08'46"	67	.137	.305	.620	2.13	— .040	
142	56'26"	10'25"	100	.0051	.0195	.049	3.10	— .182	
143	57'46"	12'06"	115	—	< .061	—	—	—	Clay
144	58'42"	13'23"	125	.006	.0235	.055	3.02	— .223	
145	59'57"	15'06"	140	—	< .061	—	—	—	Clay
146	42°00'42"	15'55"	146	.0065	.026	.055	2.91	— .276	
147	01'35"	09'52"	96	—	< .061	—	—	—	Silt
148	01'47"	09'36"	100	—	< .061	—	—	—	Silt and shells
149	01'58"	09'20"	88	—	> .061	—	—	—	Fine sand
150	02'07"	09'05"	67	—	—	—	—	—	Fine sand, silt
151	02'19"	08'49"	70	.092	.146	.830	3.01	+ .551	
152	02'29"	08'35"	34	—	> .061	—	—	—	Coarse sand
153	02'11"	08'28"	65	.014	.064	.670	6.91	+ .358	
154	01'48"	08'00"	65	.262	.418	.620	1.54	— .030	
155	01'26"	07'32"	58	.165	.436	.780	2.17	— .169	
156	02'32"	09'22"	52	—	< .061	—	—	—	Silt and clay

INTERRELATIONS OF PROPERTIES OF THE SEDIMENT

Before the characteristics of the sediments can be correlated with the factors of their environments, it is necessary to determine which of those characteristics are interdependent.

Median Diameter: Sorting.—Figure 4 shows the relationship between median diameter and sorting factor for all Cape Cod Bay samples analyzed with the exception of the beach samples and those from Provincetown Harbor, an environment which is not typical of the open bay. Most of the coarser sediments are well sorted, 85 per cent of the material coarser than 0.062 mm. having sorting factors

less than 1.75, while the finer sediments with median diameters less than 0.062 mm., all have sorting factors greater than 2.00. The same relationship was found in Buzzards Bay sediments (Hough, 1940).

In figure 4, a line was drawn to represent the general trend of distribution of points and this indicates that the degree of sorting becomes slightly better from the larger median diameters down to about 0.15 mm., then becomes markedly poorer as the diameters decrease.

Median Diameter: Skewness.—Figure 5 shows the relationship between median diameter and log of skewness for the same samples as are plotted in figure 4. The line following the general trend of

TABLE 2. *Statistical constants of beach sediments of Cape Cod Bay, Massachusetts*
(Locations of samples are shown in figure 3)

Sample No.	Locality	Statistical constants				
		Diameters in mm.			So.	Log Sk.
		Q1	Med.	Q3		
1	beach	.710	.830	.925	1.142	-.020
2	"	.678	.787	.910	1.158	-.002
3	"	.691	.830	1.005	1.204	+.004
4	"	.451	.542	.658	1.210	+.004
5A	"	.513	.607	.730	1.192	+.007
5B	cliff	.343	.442	.588	1.310	+.019
6	beach	.430	.510	.605	1.184	.000
7A	"	.447	.640	.905	1.428	+.025
7B	cliff	.395	.622	1.000	1.590	+.009
8	beach	.399	.491	.619	1.243	+.009
9	"	.406	.542	.720	1.330	.000
10	"	.351	.428	.561	1.265	+.025
11	"	.408	.628	.860	1.450	-.050
12	"	.478	.570	.682	1.194	.000
13	"	.419	.552	.740	1.328	+.007
14A	"	.383	.481	.602	1.252	.000
14B	cliff	.160	.213	.282	1.328	-.002
14C	"	.649	.908	1.380	1.457	+.035
15	beach	.540	.661	.815	1.228	+.115
16	"	.281	.310	.411	1.208	+.079
17	"	.245	.311	.432	1.327	+.215

distribution of points in this graph indicates that the log of skewness varies from a low negative value in the coarser grades to a very low positive value in the

TABLE 3. *Average sphericity and roundness of pebbles of Cape Cod Bay, Massachusetts*

Sample No.	No. of pebbles	Elevation in feet	Average sphericity	Average roundness
Beach A	81	+ 10	.661	.678
Beach B	97	+ 8	.658	.616
1	80	- 30	.707	.506
3	7	- 98	.694	.543
4	96	-110	.683	.503
6	6	-152	.675	.478
7	91	-174	.692	.415

vicinity of median diameter 0.15 mm., then becomes strongly negative as the sediment becomes finer. Whether there is a genetic relationship here is not apparent, but the observed data agree with earlier findings³ in that the finer sedi-

ments tend to become increasingly negatively skewed. Thus it is seen that in both the sorting and skewness relations to median diameter the sediments of the two bays are comparable.

Sorting: Skewness.—The relation between sorting factor and log of skewness was investigated by plotting these two functions in a graph. The result showed that the well sorted samples have an average log of skewness of zero, and the poorly sorted samples are highly skewed, in a negative direction, as would be expected from a consideration of the median: sorting and median: skewness relations.

Median Diameter: Sphericity.—The average sphericity values of the various pebble samples analyzed (table 3) have a small range of variation, from 0.658 to 0.707. No significant correlation between size and sphericity can be established in this narrow range. The relation between size and sphericity of pebbles in an individual sample (Beach B) was investi-

³ Buzzards Bay sediments, Hough, 1940.

gated, and it was found that the sphericity variation was small and random from one size grade to the next. Both the sphericity and size ranges may have been too small, however, to disclose any relationship between them.

Median Diameter: Roundness.—Roundness was found to be independent

roundness generally being less in the finer particles.

Sphericity: Roundness.—A comparison of average sphericity with average roundness for the samples studied (table 3) showed no clear interrelationship except that the beach pebbles, which are rounder than the bottom pebbles, are slightly less

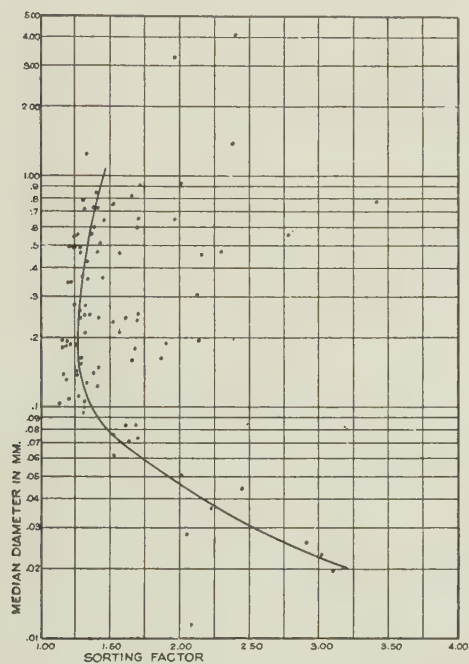


FIG. 4.—Relation between median diameter and sorting factor of Cape Cod Bay sediments.

of size in a comparison of these properties for individual pebbles of a sample as well as in a comparison of the values for all of the pebbles in all of the bottom samples. Likewise, a comparison of size and roundness of all the pebbles in all of the beach samples showed no correlation between these properties. The independence of size and roundness is unique in this suite of samples, in so far as the writer has been able to determine. Published reports dealing with these properties in other sediments indicate an interrelationship,

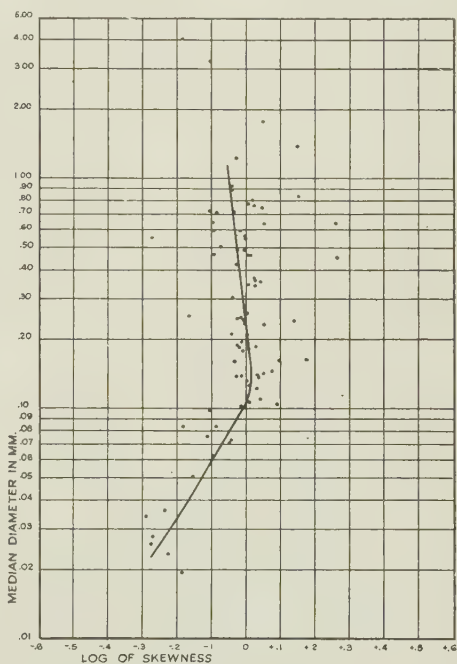


FIG. 5.—Relation between median diameter and log of skewness of Cape Cod Bay sediments.

spherical. Further comparisons were made of these two functions for individual pebbles in one of the beach samples and two of the bottom samples, and no correlation was found. Whether this lack of correlation has any genetic significance is not known.

Rock Type: Shape.—A comparison was made of the sphericity and roundness values of the various rock types in beach sample B, and very little correlation was found between these functions and lithology except that quartz is more spherical

and better rounded than the average material of the sample. Rock types were tabulated for three samples of beach pebbles collected near the tip of Cape Cod. The types and their average frequency are given in table 4.

TABLE 4. *Lithological composition of beach pebbles, Cape Cod, Massachusetts*

Rock type	Average frequency by number per cent
Granite	30
Diorite and gabbro	13
Basalt	12
Other volcanics	6
Schist	4
Slate	2
Quartzite	5
Vein quartz	22
Sandstone	2
Conglomerate	1
Chert	2
Unidentified	1
Total	100

INTERRELATIONS BETWEEN PROPERTIES OF SEDIMENT AND FACTORS OF ITS ENVIRONMENT

Depth of Water: Median Diameter.—No significant degree of correlation was found between the median diameter of a sample and the depth of water from which it was collected, when all of the data were plotted on a graph. The map, figure 3, indicates, however, that there is a degree of regularity in the distribution of the sediments in relation to their environments. Material within a certain size range is characteristic of a certain depth range within a circumscribed part of the bay. Differences in local conditions apparently are of greater importance than absolute depth in determining the characteristics of the sediment. In general, coarse-grained material may occur at any depth whereas the finest material is restricted to deep water in the open bay and to the protected embayments of the shore.

The fine sediment of type three is generally black when wet, apparently be-

cause of the reduction of iron oxides to sulfides as a result of organic decomposition. In the area northwest of Stellwagen Bank, the boundary of the fine sediment is related not to depth of water but to distance from the current-deflecting masses of the Cape and the bank. There are strong tidal flows in this area, and sands of type two are the common sediment.

Depth of Water: Sorting and Skewness.—There is no direct correlation between depth and the constants of sorting and skewness in the suite of samples as a whole. Since the finer-grained sediments are restricted to deeper water, and these are poorly sorted and highly skewed, there is a correlation between depth and the two constants in a part of the samples. A similar relationship was found in Buzzards Bay sediments.

Depth of Water: Sphericity.—The average sphericity of the pebbles shows little variation and there is no significant relationship between sphericity and depth of water. The beach pebbles are only slightly less spherical than any taken from the bottom of the bay.

Depth of Water: Roundness.—In Cape Cod Bay the beach pebbles are better rounded than the pebbles occurring on the bottom of the bay. As a general trend, roundness is less well developed with increase in depth. This is shown by the curve in figure 6 plotted from the data of table 3 in which depth and roundness are compared. Beach pebbles above the high tide line have the highest average degree of roundness, 0.678, while pebbles of the deepest sample analyzed, from 174 feet of water, have the lowest average roundness value, 0.415.

Stratification.—The core samples collected from Cape Cod Bay, though too short to provide any information on character of the sediment in relation to depth of burial, show stratification of the fine-grained deposit. As in Buzzards Bay, the layers generally range from 1 to 2 cm. in thickness and are marked either by differences in grain size or by accumulations of shells in definite horizons. Where shells are the strata-markers,

there generally are no apparent differences in grain size. Accumulation of the shells may have occurred by a process of growth of shell-secreting organisms during times of slight wave action and consequent low turbidity of the water and slow deposition of sediment, followed by burial during times of storm and rapid deposition of sediment.

Properties of the Beach Sediments and Factors of Their Environment.—Schalk (1938) has made a detailed study of the outer beach of Cape Cod which included samples taken from the stretch around the northern tip of the Cape and extending to Long Point, the recurved spit separating Provincetown Harbor from Cape Cod Bay (fig. 3). His conclusions may be summarized as follows: the cliffs of the eastern shore of the cape are the source of sediment forming the northern end of the cape, and the beach sand becomes progressively coarser in the direction of movement from the cliff section, north-westward around Race Point and south-eastward to Long Point in Cape Cod Bay. The increase in median diameter is brought about by the removal of the finer grades of sand from the beach to the water offshore. From Race Point to Long Point the median diameter grades from approximately 1.20 to 1.42 mm.

The coarsest sands of the bay beaches occur on the eastern shore opposite Long Point, about one mile southeast of Provincetown Harbor. There is a decrease in median diameter southward along the eastern shore of the bay. Certain features of this shore, particularly the bar that deflects Pamet River to the northward, indicate a northward movement of sediment. This was recognized by Davis (1896). There is, therefore, an increase in median diameter in the direction of transportation of the beach material, corresponding with that found by Schalk in the beach section extending along the outer side of the cape to Long Point.

The beach sand at Corn Hill⁴ on the

⁴ Location of beach samples are shown in figure 3.

eastern shore (Sample no. 3A, median diameter 0.607 mm.) is coarser than the material in the adjacent cliff (Sample no. 5B, median diameter 0.442 mm.), but the beach sand is better sorted and has a smaller log of skewness. Beach sample 14A, from the western shore, has a median diameter intermediate between those of two samples taken from the adjacent cliff. The beach sample is better sorted and has a lower log of skewness than the cliff samples. At all three of the above localities, the cliffs are being eroded and are contributing sediment to the beach. It is apparent that beach processes are reworking the material and are producing a better sorted, less skewed sediment. It must be remembered that all of the beach and cliff samples are composites, so that the sorting and skewness values are not representative of individual spot samples.

Transportation of Beach Pebbles.—Pebbles and cobbles up to six inches in diameter have been observed on the Wood End-Long Point beach (at the south side of Provincetown Harbor, figure 3) by several writers. This area, generally, is considered as the end of the above-water portion of Cape Cod, so far as beach transportation of sediments is concerned. The question has arisen as to the manner in which the pebbles have reached this location. Woodworth and Wigglesworth (1934) report an observation by Vaughan indicating that the pebbles may be a part of a local deposit of glacial till or outwash which is incorporated in the Cape. Vaughan subsequently has stated that he considered the pebbles of glacio-aqueous origin; that is, brought to their present position by waves or currents from a glacial deposit in the vicinity.⁵

Schalk (1938) has shown that it is possible for the pebbles to have been carried from the eastern shore of the Cape. No pebbles were found by dredging on the off-shore bottoms on the bay side of this region of the cape. Schalk concluded that

⁵ Vaughan, T. Wayland, personal communication, June 12, 1940.

they remain close to the low tide mark. His presentation is supported by the writer's observation that even at times of moderate wave action pebbles may be heard knocking against each other in the water's edge on the northern beach of Cape Cod. This indicates that pebbles are moved along the beach in this area.

The "Hard Bottom" Zone.—Trowbridge and Shepard (1932) described a hard bottom zone paralleling the shore of Massachusetts Bay and extending southward to Cape Cod Bay. They indicated that the zone might contain either bed rock or large rock fragments, but favored the postulate of the occurrence of bed rock. It was suggested by them that any finer-grained material that previously had covered the zone was either scraped away by the continental ice sheet or washed away at a time of lowered sea level.

The writer (1932), in a discussion of this paper, suggested that the rock bottom zone contains boulders of glacial origin left as a lag concentrate by erosion occurring principally while the sea stood at its present elevation. In Lake Michigan the writer found a concentrate of pebbles which was sufficiently thin in some places to be penetrated by a coring tube which brought up undisturbed glacial till from below the pebbles. Some of the pebbles in the Lake Michigan concentrates showed glacial striae, which indicates that they have not been subjected to any appreciable wear since their deposition from the glacial ice.

Stetson and Schalk (1935, p. 40) reach the conclusion that "in Massachusetts Bay there is a belt of subangular pebbles roughly paralleling the shore which is a lag concentrate formed by the washing out of the finer constituents of fluvio-glacial deposits" and stated that "it is obvious that the . . . pebbles have never been on any beach and that they are being little abraded in their present position."

In Cape Cod Bay, the "rock bottom" zone consists of the area occupied by sediments of type one, as previously de-

scribed for the northwestern part of the bay. Only a small number of samples were collected in the area, but at every sampling station coarse sand or larger sedimentary particles were found. Shape studies of the larger particles indicate that no appreciable rounding of particles has taken place.

It is interesting to compare the data of table 3 with roundness values for the

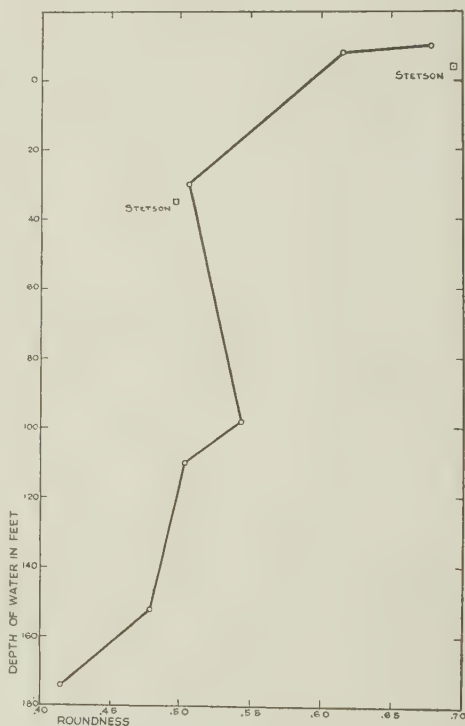


FIG. 6.—Relation between depth of water and roundness of Cape Cod Bay sediments.

two samples illustrated in figure 2 of Stetson's and Schalk's paper (1935). One of these is a sample from the beach at Cohasset and the other is from the subangular pebble zone of Massachusetts Bay offshore from Cohasset Beach. From enlarged reproductions of these illustrations, the writer determined roundness values which are plotted in figure 6 and labelled "Stetson." They lie close to the line drawn through the writer's data and

conform to the roundness values for samples from similar localities in Cape Cod Bay. The conclusions of Stetson and Schalk in regard to this zone in Massachusetts Bay thus were verified for Cape Cod Bay, and their detailed description of the zone may be considered as applying equally well to the same feature in Cape Cod Bay in their manner of formation.

Abrasion of Pebbles.—It appears that the rigor of processes operating in the bay and the time during which they have operated have not been great enough to alter the sphericity of the pebbles appreciably. Wave action, however, apparently has been competent to round their corners. The greater roundness of the beach and shallow water pebbles may be considered as a result of abrasion rather than selective transportation, because all of the pebbles in the bay have a common source in the glacial deposits and the more highly rounded individuals in the samples having high average roundness values are rounder than any of the individuals in the bottom samples having low average roundness values.

Considering both roundness and sphericity values, it appears that at least the coarser particles of sediment have undergone relatively little abrasion, even in the shallower water where the corners have been rounded to only a barely significant degree. Abrasion of pebbles, therefore, has not been an important source of finer-grained sediment.

In a study of the quantities of material of various sizes which are present in the Bay, the median diameters of all analyzed samples (tables 1 and 2) were plotted on a bar diagram similar to that in figure 9, and the median diameters of all the samples from Buzzards Bay (Hough, 1940, pp. 23–26) were added to the diagram to form figure 9. This combination of data was made in order to present a larger number of samples, and is permissible because the two bays are adjacent bodies of water deriving their sediments from the same source materials. The data for the two areas give sim-

ilar diagrams when plotted separately. In figure 9, the number of samples having median diameters in each of the size ranges indicated is shown.

There is a relative scarcity of sediment

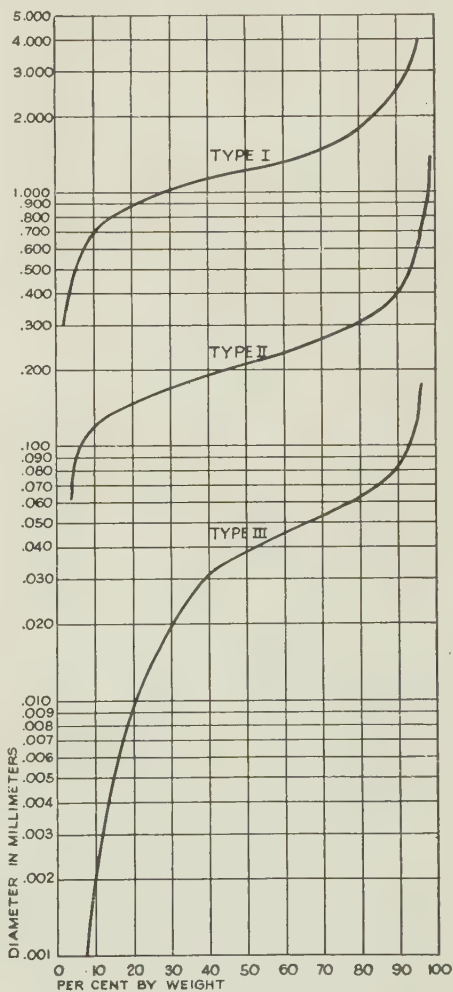


FIG. 7.—Grain-size distribution curves of samples representing the three types of bottom sediment in Cape Cod Bay. (Samples 23, 27 and 139.)

ilar in the size ranges between 2.83 and 2 mm. and between 0.062 and 0.044 mm. A low frequency of material at the same points on the size scale has been observed in

suites of samples from other areas.⁶ The significance of the low frequency in the granule sizes is interpreted as follows: above the granule size the sedimentary particles consist largely of rock fragments made up of several mineral grains, while below the granule size the particles consist largely of individual mineral grains. Within the granule size the particles are constituted of only a few mineral grains, perhaps two to four or five. Such a particle is rather unstable because of the few bonds between crystals, and tends to break down rapidly. The coarser material, then, when it is diminished to about 4 mm. in diameter, is broken down rapidly to the size of the individual crystals after which the grains again are relatively resistant to wear.

In the writer's tentative explanation of low frequency in the coarse silt range, consideration is given to the experiments

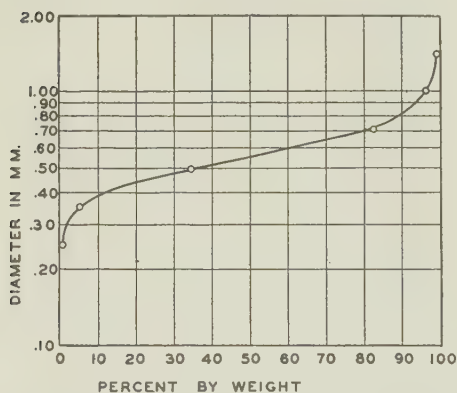


FIG. 8.—Grain-size distribution curve of sample representing the beach sediments of Cape Cod Bay. (Beach sample No. 4.)

of Marshall and others summarized in the *Treatise on Sedimentation* (Twenhofel, et al., 1932, pp. 9-11); these indicate that the work of rock disintegration tends to

⁶ A scarcity of material in the 4 to 2 mm. diameter range was brought to the writer's attention by Pettijohn (personal communication), and a scarcity of material in the coarse silt range in other suites of samples has been noted by Rittenhouse (personal communication).

produce particles of the size of the original mineral grains, while abrasion occurring in water or air does not produce fine sand or coarse silt, but tends to produce rock flour by the breaking off of

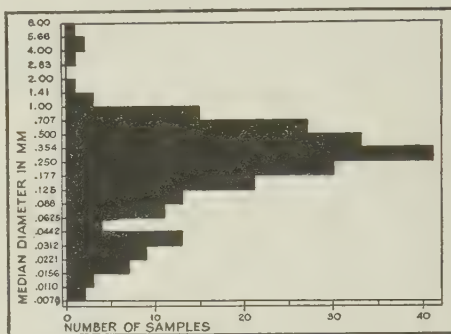


FIG. 9.—Median diameter distribution of Cape Cod Bay and Buzzards Bay sediments.

fragments considerably smaller than the parent grains. Thus a low frequency of material in the coarse silt range might be expected. Grinding in glacial ice may conceivably result in the formation of a somewhat coarser product, so that the frequency of the Cape Cod material is not inconsistent with the deductions from the experiments quoted.

SUMMARY OF THE CHARACTERISTICS OF CAPE COD BAY SEDIMENTS

Very little sediment has been added to the bay from outside the area since glacial times and the recent sediments are composed of materials derived within the area, principally through erosion of unconsolidated materials of the shores. The nature of the above-water and shallow-water materials subject to erosion and the sorting, wear and redeposition of the materials have determined the characteristics of the recent deposits. Over the bay as a whole, abrasion has been of questionable importance in modification of the size of particles but in the zones of more intense wave action a small amount of rounding with consequent reduction in size has taken place. Organic decomposition has affected the finer-grained sedi-

ments in particular, giving them a dark color probably through reduction of iron oxides to sulfides.

A representative individual sample from each of the three types of bottom sediment will serve to characterize the mechanical composition of the bottom sediments. The cumulative curves of these are shown in figure 7 and their statistical constants are listed below:

	Median diameter in mm.	Sorting factor	Log of skewness
Type I	1.225	1.33	-0.030
Type II	0.210	1.32	+0.008
Type III	0.0365	2.22	-0.236

A representative beach sample was selected from the Cape Cod Bay suite on the basis of its intermediate position in regard to median diameter, sorting and skewness values. The cumulative curve for this sample is shown in figure 8, and its statistical constants are listed below:

	Median diameter in mm.	Sorting factor	Log of skewness
Beach sample No. 4	0.542	1.21	+0.004

The rock types which constitute the larger sedimentary particles and the mineralogical composition of the finer sediments reflect the known source of the glacial materials in the land area to the north where igneous and metamorphic rocks predominate.

The bulk of the bay sediment probably has been through two sedimentary cycles; during one it was moved from the crystalline rock terrain to the bay area by the continental ice sheet, and during the other, it was removed from the glacial deposits and redistributed by waves and currents to form the recent sediments.

In the bay, coarse-grained particles have tended to remain near their sources or, in the case of the beach materials, to remain within the zone of intense wave action in shallow water, while fine-grained particles have been moved to areas of deeper water.

COMPARISON OF CAPE COD BAY SEDIMENTS WITH THOSE OF OTHER BAYS

Buzzards Bay.—The sediments of the two bays are generally similar in their characteristics and distribution. Comparisons of material in the two areas have been made at various points in the present paper, and reference to the earlier paper on Buzzards Bay (Hough, 1940) will indicate that the summary of properties and relationships of Cape Cod Bay sediments is generally applicable to those of Buzzards Bay sediments.

Massachusetts Bay.—The article of Trowbridge and Shepard (1932) gives complete mechanical analyses of only 20 samples, in the sand range, and partial analyses of 44 others not including the finest sediments. It is impossible, therefore, to compare statistical constants of the various types of sediment in Massachusetts Bay with those for Buzzards Bay and Cape Cod Bay.

Distribution of sediment types in Massachusetts Bay is similar to that in Cape Cod Bay. The types illustrated in the map published by Trowbridge and Shepard were combined to form the three types set up in the present report. The "rocky" zone and the "sand and gravel" zone of Massachusetts Bay, when combined, are comparable to type one sediments of Cape Cod Bay and the zone of such material is continuous from the northwestern shore of Massachusetts Bay to the southwestern part of Cape Cod Bay.

A composite histogram of the 64 samples analyzed by Trowbridge and Shepard shows a low frequency of material in the granule size, 1 to 2 mm., corresponding to that found in the Buzzards Bay and Cape Cod Bay sediments. The possible significance of this low frequency has been discussed above. Trowbridge and Shepard explained this low frequency as being a gap between two sediment loads, one moved by storm waves and the other moved by more gentle waves. The writer has explained it as a result of in-

stability of compound particles made up of only a few mineral grains.

San Francisco Bay.—In San Francisco Bay (Louderback, 1939) there are two types of sediment distribution; one, in which grain size decreases with depth of water and distance from certain elements of the shore lines, and another in which the coarseness increases with depth of water. These distributions are related to the peculiar form of the bay and its relation to waves and tidal currents. The deep, narrow channel connecting the central part of the bay with the Pacific Ocean is swept by strong tidal currents which decrease in intensity toward the margins of the bay. In the shallower water near shore, coarser particles are concentrated near sources in headlands exposed to wave action, while progressively finer material, apparently derived from the headlands by wave erosion, is found in progressively deeper water down to a certain level which is comparatively shallow. Below this depth, the second type of distribution occurs, a progression from finer sediments to coarser ones with increasing depth, and this distribution is brought about by tidal transportation and deposition of material brought to the bay largely by the major tributary streams. This second type of distribution is characteristic of the larger area of the bay by far.

In both Buzzards Bay and Cape Cod Bay, there are localities in shallow water in which the grain size decreases with depth, and which are comparable with the first type of distribution of sediments in San Francisco Bay. Near the mouth of Buzzards Bay and in the area adjacent to the tip of Cape Cod in Cape Cod Bay, there are deep channels in which relatively strong tidal currents flow. The physical environments of these portions of the two bays are comparable with that of the greater part of San Francisco Bay, and the sediment distributions are likewise similar.

The tidal marshes of San Francisco Bay contain the finest-grained sediments that were sampled. Tidal marshes and

protected inlets in the Cape Cod area also contain very fine material.

Barataria Bay.—Barataria Bay, on the Gulf Coast, studied by Krumbein and Aberdeen (1937), is comparable to the smaller embayments of the Cape Cod region. Plymouth and Duxbury Bays, on the western shore of Cape Cod Bay, have a similar system of tidal channels in a shallow body of water floored with fine-grained sediment. The sedimentary particles present in Barataria Bay are, on the whole, much smaller than those in Buzzards Bay and Cape Cod Bay. In all three bays, however, there is a consistent relationship between size and sorting; the finer sediments are progressively more poorly sorted. In Barataria Bay, as in the deeper part of San Francisco Bay, and in the deeper channels at the mouths of Buzzards Bay and Cape Cod Bay, the size of sedimentary particles increases with increasing depth. A greater strength of tidal currents is the determining factor in each locality.

Statistical constants of comparable sediment types in Barataria Bay and in Cape Cod Bay are similar, as is shown in the following tabulation:

Sedi- ment type	Location	Median diam- eter in mm.	Sort- ing factor	Log of skew- ness
I	Barataria Bay	0.139	1.18	-0.04
II	Cape Cod Bay	0.210	1.32	+0.008
IV	Barataria Bay	0.040	2.33	-0.39
III	Cape Cod Bay	0.0365	2.22	-0.236

Continental Shelf Sediments.—Sediments of the Continental Shelf, as described by Stetson (1938), generally are coarser in relation to depth than are those of Buzzards Bay and Cape Cod Bay (excluding the lag sediments of the bays), as is consistent with the more exposed nature of the shelf environment. A comparison of sediments of the same median di-

ameter, however, indicates that the constants for sorting and skewness are of the same order of magnitude. For example, samples representative of types one and three sediment in the bays and samples representative of two wide zones on the Continental Shelf off Marthas Vineyard have the following constants:

Location	Median diameter in mm.	Sorting factor	Log of skewness
Cape Cod Bay	0.210	1.32	+0.008
Continental Shelf	0.210	1.35	+0.020
Cape Cod Bay	0.0365	2.22	-0.236
Continental Shelf	0.034	2.82	-0.340

There is a remarkable similarity in the sorting and skewness values of sediments from the two environments, when samples with approximately the same median diameter are compared. This suggests that similar marine processes, when they are of the same rigor (as indicated by the median diameter), produce similar size distributions of the sediment.

The same relationships do not occur in a comparison of the fine-grained sediments of the two bays studied with those of the Baltic (Gripenberg, 1939); the Baltic material is finer-grained and has positive logs of skewness.

GEOLOGIC SIGNIFICANCE OF THE BAY SEDIMENTS

The chances for survival of the sediments of bays like those studied are problemetical. Shallow water marine sediments make up a considerable part of the geological record, but most of them were laid down in extensive inland seas rather than close to the border of a continent. It is likely that sediments similar to those of the bays, deposited in corresponding depths and subject to waves and currents of comparable rigor, have been preserved and it may be of value, therefore, to postulate the types of consolidated rocks which might be formed from the bay sediments.

The fine-grained black sediments of the deeper waters would form stratified shales with a dark color, perhaps with a small quantity of organic matter. They would contain iron sulfide minerals and, in the case of the sediment in the southern part of Buzzards Bay, possibly some glauconite. Flakes of micaceous minerals deposited parallel to the bedding would give a typical shaly parting. Stratification of the deposit would be marked both by differences in grain size and by alignment of fossils. The shells in the deposit apparently have accumulated through a process of growth during times of quiescent wave action and burial when large quantities of sediment were deposited. In the fine-grained sediments the shells are generally small, fragile forms which show little evidence of mechanical wear. Solution taking place within the deposit may remove a considerable part of the shell material, however, before lithification is complete. The well-sorted, clean sands, which contain fragments of shells in some places, may form a typical sterile sandstone if solution of the carbonates is completed before the sand is cemented. Structures such as ripple marks in the shallower deposits would be preserved.

Pebble concentrates of the bays, occurring in as deep as 170 feet of water, might be mistaken for beach deposits in a cursory examination. A study of the roundness of the pebbles would serve, however, to distinguish between the beach and the bottom pebbles.

If the record preserved were fragmentary, the occurrence of muds over the fluvio-glacial sands would appear to represent only a minor stratigraphic break, whereas it actually represents a significant change in conditions of deposition.

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REFERENCES

- ALEXANDER, A. E., 1934, A petrographic and petrologic study of some Continental Shelf sediments: *Journal Sedimentary Petrology*, vol. 4, pp. 12-22.
- DAVIS, W. M., 1896, The outline of Cape Cod: *Am. Acad. Arts and Sci., Proc.*, vol. 41, pp. 303-332.
- GALLIHER, E. W., 1935, Geology of glauconite: *Am. Assoc. Pet. Geol. Bull.* vol. 19, pp. 1569-1601.
- HOUGH, J. L., 1932, Suggestion regarding the origin of rock-bottom areas in Massachusetts Bay: *Journal Sedimentary Petrology*, vol. 2, pp. 131-132.
- , 1935, The bottom sediments of southern Lake Michigan: *Journal Sedimentary Petrology*, vol. 5, pp. 57-80.
- , 1939, Bottom sampling apparatus: *Recent Marine Sediments*, Am. Assoc. Petroleum Geol., Tulsa, pp. 631-664.
- , 1940, Sediments of Buzzards Bay, Massachusetts: *Journal Sedimentary Petrology*, vol. 10, pp. 19-32.
- KRUMBEIN, W. C., 1934, The probable error of sampling sediments for mechanical analysis: *Am. Journal Science*, vol. 27, pp. 204-214.
- , and ABERDEEN, E., 1937, The sediments of Barataria Bay: *Journal Sedimentary Petrology*, vol. 7, pp. 3-17.
- , and PETTIJOHN, F. J., 1938, *Manual of Sedimentary Petrology*, D. Appleton-Century, pp. 137-142 and 162-172.
- LOUDERBACK, G. D., 1939, San Francisco Bay sediments: *Proc. Sixth Pacific Science Congress*, pp. 783-793.
- OTTO, G. H., 1933, Comparative tests of several methods of sampling heavy mineral concentrates: *Journal Sedimentary Petrology*, vol. 3, p. 32.
- SCHALK, M., 1938, A textural study of the outer beach of Cape Cod: *Journal Sedimentary Petrology*, vol. 8, pp. 41-54.
- STETSON, H. C., and SCHALK, M., 1935, Marine erosion of glacial deposits in Massachusetts Bay: *Journal Sedimentary Petrology*, vol. 5, pp. 40-51.
- TRASK, P. D., 1932, *Origin and Environment of Source Sediments of Petroleum*, Gulf Publ. Co., Houston, pp. 68-76.
- TROWBRIDGE, A. C., and SHEPARD, F. P., 1932, Sedimentation in Massachusetts Bay: *Journal Sedimentary Petrology*, vol. 2, pp. 3-37.
- TWENHOFEL, W. H., et al., 1932, *Treatise on Sedimentation*, 2nd. Ed., The Williams and Wilkins Co., Baltimore, pp. 9-11.
- VEATCH, A. C., 1906, Outlines of the geology of Long Island: *U. S. Geol. Survey*, Prof. Paper 44, pp. 26-32.
- WOODWORTH, J. B., and WIGGLESWORTH, E., 1934, The geology of Cape Cod and the New England Islands: *Mus. Comp. Zool., Mem.*, vol. 52.

